Whole-Body vibration comfort measurement aboard the S.A. Agulhas II and just noticeable difference threshold testing in the laboratory

by

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Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering (Mechanical) in the Faculty of Engineering at Stellenbosch University

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December 2014

Declaration

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Abstract

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Thesis: MEng (Mechanical)

December 2014

A continuous comfort analysis of the whole-body vibration level aboard the S.A. Agulhas II during the 2013-2014 Antarctic voyage was conducted according BS ISO 2631-1:1997, assuming a standing posture. Just noticeable difference in magnitude testing was conducted on nine subject in the standing posture on a man-rated shaker in the laboratory environment. Two stimuli, a 5 Hz sinusoidal stimulus with a magnitude of 0,5 $m{\cdot}s^{-2}$ and a slamming event recoded during the voyage with a magnitude of 0,2 $m{\cdot}s^{-2}$ where selected as the stimuli on which to investigate the just noticeable difference threshold. The study shows that the vibration level for the duration of the voyage can be considered to be not uncomfortable. The results of the just noticeable difference threshold obtained for the sinusoidal stimulus concur with that found in literature for seated subjects. The just noticeable difference threshold obtained for the ship stimulus does not correlate with the results for the sinusoidal vibration, implying that there may be an error in the vertical weighting filter provided by the standard or that Webers law does not hold for the just noticeable difference threshold of standing subjects.

Uittreksel

Hele liggaam vibrasie gemak meting aan boord van die S.A. Agulhas II en net opvallende verskil drumpel toets in die laboratorium

("Whole-Body vibration comfort measurement aboard the S.A. Agulhas II and just noticeable difference threshold testing in the laboratory")

K. McMahon

Tesis: MIng (Meganies)

Desember 2014

'n Deurloopnede gemakanalise van volliggaam vibrasievlakke aanboord die S.A. Agulhas II is uitgevoer. Die analise tydens die 2013-2014 Antarktiese reis is gedoen volgens BS ISO 2631-1 : 1997 vir 'n staande postuur. 'n Net-opmerkbare-verskildrempel toets is uitgevoer op nege vrywillers in 'n staande postuur deur vibrasieherkonstruksie op 'n platform in die laboratorium. Twee stumuli, 'n 5 Hz sinusvorminge stimulus (0,5 $m{\cdot}s^{-2}$ r.m.s.) en 'n branderimpak stimulus (wat tydens die reis opgeneem is, 0,2 $m{\cdot}s^{-2}$ r.m.s. is gebruik) om die net-opmerkbare-verskildrempel to ondersoek. Die studie toon dat die vibrasievlakke gedeurende die reis as 'nie ongemaklik' geklassifiseer kan word. Die resulte van die net-opmerkbare-verskildrempel verkry vir die sinusvormige stimulus stem saam met bevindinge vir sittende vrywilligers uit die literatuur. Die net-opmerkbare-verskildrempel verkry vir die skip stimulus stem egter nie 'n moonlike onakkuraatheid weegfunksie is wat deur die standard is aanbeveel word of dat Weber se wet nie toepaslik is vir die net-opmerkbare-verskildrempel van staande vreywilligers nie.

Acknowledgements

I would like to express my sincere gratitude to the following people and organisations:

- Marcel Erasmus for her constant constant care and loving that she provided throughout the project
- Keith Soal for helping with many of the technical and theoretical details
- Ferdie Zietsman for his help with the technical aspects of the project
- Dr. A Bekker for providing guidance and input into the project
- National Research Foundation and Department of Science and Technology under the South African National Antarctic Programme for project funding
- The Department of Environmental Affairs for allowing for the measurement on the ship

Dedications

This thesis is dedicated to Sun Tsu 'Steven' Tseng

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Nomenclature

Variables

W_k	Vertical weighting filter	[ ]
W_d	Horizontal weighting filter	[ ]
$a_w(t)$	Weighted descretly sampled acceleration	[$\mathrm{m \cdot s^{-2}}$]
a_w	Weighted r.m.s acceleration acceleration	[$\mathrm{m \cdot s^{-2}}$r.m.s.]
f_s	Sampling frequency	[Hz]
I	Reference stimulus magnetude	[$\mathrm{m \cdot s^{-2}}$r.m.s.]
$\triangle I$	just noticeable differecne magnetude	[$\mathrm{m \cdot s^{-2}}$r.m.s.]
H_{est}	transmissibility estimate	[ ]
S	Fast Fourier transform of acceleration signal	[$\mathrm{m \cdot s^{-2}}$]

Acronyms

BS British Standard

ISO International Organisation for Standardisation

DNV Det Norske Veritas

DEA Department of Environmental Affairs

JND Just Noticeable Difference

UDTR Up-Down-Transformed-Response

r.m.s. Root Mean Square

VDV Vibration Dose Value

IIR Infinite Impulse Response

SDS Scientific Data System

DSTF Dynamic Seat Testing Facility

LVDT Linear Variable Displacement Transducer

DP Dynamic Positioning

PSD Power Spectral Density

Chapter 1

Introduction

During transportation the passengers and drivers are exposed to mechanical vibration which can lead to discomfort and possibly negative health effects. Research of whole-body vibration has been conducted to better understand the relationship between vibration and the discomfort, negative health effects and motion sickness that may arise from an exposure to such vibration. Based on the research conducted, standards such as BS ISO 2631-1 (1997) (which may from here on be referred to as ISO 2631-1) and BS 6841:1987 have been published to aid in the evaluation of vibration with respect to perception, health effects, comfort and motion sickness.

The S.A. Agulhas II is a South African polar supply and research vessel with icebreaking capabilities. Det Norske Veritas (DVN) classified the ship with a Polar Class 5 ice rating, meaning that she was designed for year-round operation in medium first-year ice which may include old ice inclusions. The vessel was classified to have intermediate comfort (COMF-V(2)) for noise and vibration by DNV.

She was built in 2012 for the Department of Environmental Affairs (DEA) by STX Finland Rauma shipyard, to carry out both scientific research and logistical support to the Antarctica, Marion island and Gough island. As such a large portion of the sailing time is sent in the Southern Ocean, which is well known for large swell heights and rough seas. During the 2013 voyage to Marion island, swells of up to eleven meters high were encountered. A large percentage of the time during the Marion voyage is spent with the ship holding a set position while offloading. During the voyages to Antarctica, the ship is required to sail through both ice of up to three meters and open seas with swell heights of up to eight meters.

The vessel is designed with a raised transom (surface that forms the stern of the vessel). This allowed for greater deck area on the stern of the ship for additional laboratory space and scientific cargo storage. A disadvantage of a raised transom is that it is susceptible to slamming events. A slam may occur when a swell or wave hits the aft of the ship, exposing the ship structure to a high impact force. This causes large vibration levels throughout the ship structure. The captain and crew complained of disconcerting vibration experiences during the 2013 voyage to Marion Island when waves slam the aft deck of the vessel, while at rest in open water (Bekker, 2013*a*). The experience was described as impact with vibration resonating for between 20 to 30 seconds. The crew and captain complained that they have difficulty sleeping when slamming is occurring, and that it also interferes with motor activities such as writing.

Daily tasks on board the ship include the general maintenance of the ship and the filling in of numerous details in log books and other such documentation by the crew and captain of the ship. Some of the researchers are on board the ship merely as passengers and thus spend most of the days reading, using laptop computers or watching TV. Other researchers perform research during the journey. The majority of which is oceanographic research that requires analysis of sea water samples in specialised laboratories located on the ship. These tasks require substantial fine motor skills in order to be carried and thus the vibrations due to slamming interfere with these tasks.

Motivated by these complaints, the Sound and Vibration Research Group at Stellenbosch University performed slamming measurements on the S.A. Agulhas II as schedules during the final acceptance trials of a deep coring system on the vessel from 28 to 31 May 2013. The results from the measurement showed that during an instance of slamming on the ship hull, the comfort class limits for standard cabins on passenger ships was exceeded (Bekker, 2013*a*).

Soal and Bekker (2013) conducted a study in which the whole-body vibration comfort of standing persons was measured on-board the S.A. Agulhas II during the 2012-2013 Antarctic voyage. The study was based on tri-axial vibration measurements in the Bridge and reported on specific case studies such as pack ice, carving, ramming, engines only, open water - rough weather and open water - calm weather, however, an evaluation of slamming was not presented in this study.

If the owners of the ship where to improve comfort aboard the vessel, the Just Noticeable Difference (JND) in magnitude threshold would be an important factor the design of the modification to the vessel as they afford the designer with an estimate for the smallest change in vibration level that a person on the ship would be able to feel. In literature JND thresholds have been assessed for a variety of stimuli, including pure sinusoidal and multi frequency stimuli, for seated subjects. No studies in literature were found investigating whole-body vibration JND thresholds for standing subjects.

As such the goals of this project were to:

- further investigate the whole-body vibration comfort of a person with a standing posture aboard the S.A. Agulhas II
- preform a study that investigates the relationship between the JND thresholds for seated subject and standing subjects

- investigate the JND threshold of standing persons exposed to vibration as measured aboard the S.A. Agulhas II

Further investigation of the whole-body comfort aboard the S.A. Agulhas II were conducted during the 11 week Antarctic 2013-2014 voyage between Cape Town, Antarctica, South Georgia and the South Sandwich Islands. The voyage included sailing in open seas as well as in ice. Continuous tri-axial vibration measurements where conducted in two measurement locations, one in the Bridge and one in the Operations Room. Human vibration exposure was assessed according to the methodology outlined in ISO 2631-1. The vibration exposure levels for 64 days of the 78 day journey are reported along with insight into specific sailing conditions.

JND threshold testing was conducted on standing subjects using the Up-Down-Transformed-Response (UDTR) procedure in a laboratory environment on a man-rated shaker platform. The JND threshold for two 4 second stimuli, a 5 Hz 0,5 m·s^{-2} r.m.s. sinusoidal stimulus and a vibration that was recoded during the voyage.

This document continues to Chapter 2 which states the relevant standards and existing JND threshold evaluations obtained through a comprehensive literature survey. The experimental setup aboard the S.A. Agulhas II during the Antarctic 2013-2014 voyage, details of the voyage and details of the man-rated shaker are summarised in Chapter 3. The method used to recreate vibration on the man-rated shaker is discussed in Chapter 4. Results of the comfort analysis and JND threshold obtained for the sinusoidal and ship stimuli are presented in Chapter 5, while Chapter 6 concludes the document with a summary of important results and recommendation for future research based on the findings.

Chapter 2

Literature study

This Chapter provides a comprehensive summary of previous works that have been published on Just Noticeable Difference thresholds. In order to discuss the previous works, some fundamental theory is established to build a basis from which to work on. The chapter then continues by describing the applications and importance of the research, followed by the previous studies on just noticeable difference thresholds and the techniques used to test for just noticeable difference thresholds. Studies relating to the comfort aboard the S.A. Agulhas II are also discussed.

2.1 Vibration measurement standard: BS-ISO 2631-1:1997

The ISO 2631-1 specifies the methodology for the evaluation of whole-body vibration with respect to comfort, human health, probability of vibration perception and incidence of motion sickness. The standard states that the primary quantity of vibration magnitude should be in acceleration, reported in $\mathrm{m{\cdot}s^{-2}}$ r.m.s. for translational measurements (BS ISO 2631-1, 1997).

2.1.1 Vibration measurement

Vibration shall be measured according to a co-ordinate system originating at the interface between human body and the vibrating surface. The axes of the vibration measurement transducers should be lined up with the basicentric axes shown in Figure 2.1.

2.1.2 Frequency weighting

The dynamic response and comfort of the human body to a given vibration differs depending on the frequency, position and direction of the vibration (Griffin, 1996). The frequency weighting allows one vibration to be compared

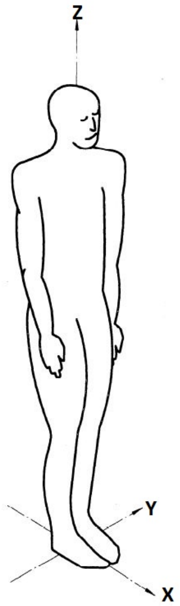


Figure 2.1: Basicentric axes of the human body in a standing position (BS ISO 2631-1, 1997)

to another in terms of discomfort, thus accounting for this frequency dependence. The standard specifies the W_k frequency weighting for the vertical (Z) direction and W_d for the horizontal (X & Y) directions.

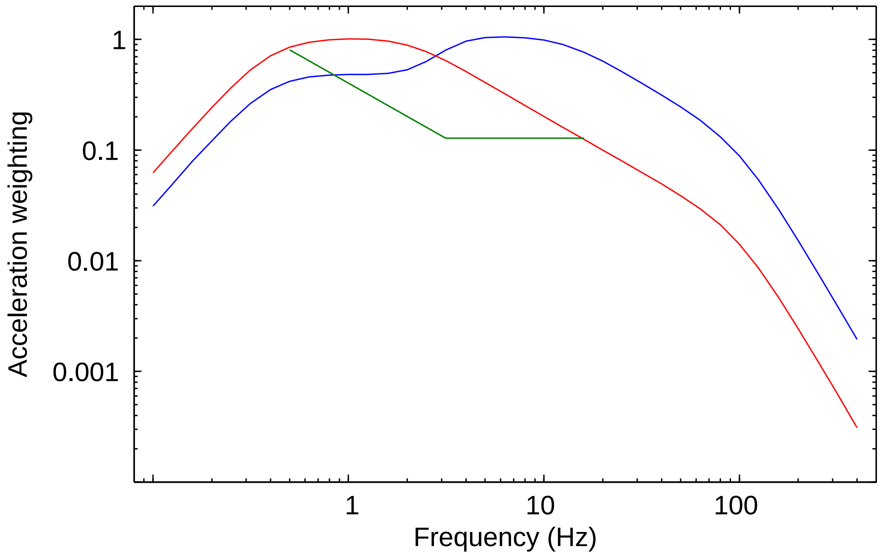


Figure 2.2: Frequency weighting curves: — : ISO 2631-1 W_k (vertical) filter; — : ISO 2631-1 W_d (horizontal) filter; —: Thuong and Griffin (2011) horizontal filter.

For the evaluation of comfort and perception, the W_k weighting is applied to the vertical (Z) direction vibration and the W_d weighting is applied to the horizontal (X and Y) directions.

The frequency weightings are constructed by cascading a number of different filters such as high pass, low pass, acceleration-velocity transition and upwards step filters to achieve the overall weighting filter. ISO 2631-1 provides the mathematical definition of the different filters and their respective transfer function parameters in the analogue 's' domain (Thuong and Griffin, 2011).

The high pass (H_h), low pass (H_l), Acceleration-velocity transition (H_t) and the upward step (H_s) filters are presented in equations 2.1.1 to 2.1.4.

$$H_h(s) = \frac{s^2}{s^2 + \frac{w_1}{Q_1}s + w_1^2} \tag{2.1.1}$$

$$H_l(s) = \frac{w_2^2}{s^2 + \frac{w_2}{Q_2}s + w_2^2} \tag{2.1.2}$$

$$H_t(s) = \frac{\frac{w_4^2}{w_3}s + w_4^2}{s^2 + \frac{w_4}{Q_4}s + w_4^2} \tag{2.1.3}$$

$$H_s(s) = \frac{s^2 + \frac{w_5^2}{w_5}s + w_5^2}{s^2 + \frac{w_6}{Q_6}s + w_6^2} \tag{2.1.4}$$

Where the constants w_i and Q_i are provided as shown in Table 2.1. The cascade for total weighting filters are defined in Table 2.2

Table 2.1: Numeric values to be used for Equations: 2.1.1 to 2.1.4. Note: $w = 2\pi f$

	H_h		H_l		H_t			H_s			
	f_1 (Hz)	Q_1	f_2 (Hz)	Q_2	f_3 (Hz)	f_4 (Hz)	Q_4	f_5 (Hz)	Q_5	f_6 (Hz)	Q_6
W_k	0.4	$\frac{1}{\sqrt{2}}$	100	$\frac{1}{\sqrt{2}}$	12.5	12.5	0.63	2.37	0.91	5.3	0.91
W_d	0.4	$\frac{1}{\sqrt{2}}$	100	$\frac{1}{\sqrt{2}}$	2	2	0.63	–	–	–	–

Table 2.2: Frequency weighting created from cascading filters

Filter	Filter stages
W_k	$H_h(s)H_l(s)H_t(s)H_s(s)$
W_d	$H_h(s)H_l(s)H_t(s)$

A method for applying the frequency weightings to measured acceleration data, in the time domain, is, however not provided in the standard (Rimell and

Mansfield, 2007). The details of a technique proposed by Rimell and Mansfield (2007) to apply the frequency weightings to acceleration data discreetly sampled in the time domain are given in Section 2.3.

2.1.3 Whole-body vibration metrics

Since the comfort of whole body vibration is strongly dependent on vibration magnitude (Griffin, 1996), it is important to define a set of metrics that can quantify vibration magnitude. The primary metric is the Root Mean Square (r.m.s.) acceleration value, which is the generally preferred unit to quantify vibration magnitude (Griffin, 1996). The r.m.s. acceleration value is determined from:

$$a_w = \left[\frac{1}{T}\sum_{t=0}^{T} a_w^2(t)\cdot\frac{1}{f_s}\right]^{\frac{1}{2}} \tag{2.1.5}$$

Where $a_w(t)$ is the weighted discreetly sampled acceleration, T is the duration of the measurement, f_s is the sampling frequency in Hz and a_w is the weighted r.m.s. acceleration value with units m·s^{-2}.

The crest factor reflects the impulsiveness of the vibration and is defined as:

$$Crestfactor = \frac{MAX(a_w(t))}{a_w} \tag{2.1.6}$$

The standard suggests that for vibrations with crest factors above 9 the use of the r.m.s. metric is not warranted as the signal is no longer considered to be a stationary random signal. Therefore the r.m.s. metric is no longer a good representation of the signal magnitude and thus the associated human comfort. Additional metrics are provided for the evaluation of vibration with high crest factors.

The fourth power vibration dose value (VDV) which has a unit of m·s$^{-1{,}75}$ is defined as:

$$VDV = \left[\sum_{t=0}^{T} a_w^4(t)\cdot\frac{1}{f_s}\right]^{\frac{1}{4}} \tag{2.1.7}$$

Whereas the r.m.s. vibration metric is not dependant on time, the VDV accumulates with exposure duration. The value of the VDV may be considered to be the magnitude of a one second motion which has an equivalent effect (Griffin, 1996). The VDV method is more sensitive to impulsive vibration than the r.m.s. method by using the fourth power instead of the second power of the acceleration time history as the basis for averaging. The standard specifies that for vibration with high crest factors (above 9) the basic (r.m.s.) values and additional (VDV) value should be reported.

The vibration total value for a given measurement position is determined from weighted vibration in orthogonal coordinates and is defined as:

$$a_v = \left(k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right)^{\frac{1}{2}} \tag{2.1.8}$$

Where a_{wx}, a_{wy} and a_{wz} are the weighted r.m.s. values for the X,Y and Z directions respectively. For the standing position, the standard specifies $k_x = k_y = k_z = 1$.

Where the comfort is affected by vibrations in more than one point, the overall vibration total value is calculated as the root sum of squares of the vibration total values for that point. The assessment of comfort is to be based on the overall vibration total value. ISO 2631-1 provides a list of likely reactions to various overall vibration total values in public transport, as provided in Table 2.3.

Table 2.3: Likely reactions to various overall vibration total values

Overall vibration total value (m·s^{-2} r.m.s.)	Likely reaction
less than 0,315	not uncomfortable
0,315 to 0,63	a little uncomfortable
0,5 to 1	fairly uncomfortable
0,8 to 1,6	uncomfortable
1,25 to 2,5	very uncomfortable
greater than 2	extremely uncomfortable

The assessment of the perceptibility of vibration is made with respect to the maximum peak weighted acceleration determined in any axis for the given measurement interval. ISO 2631-1 suggests that there is a large variation between individuals in their ability to perceive vibration, with a median perception threshold of approximately 0,015 m·s^{-2} while the interquartile range extending from 0,01 m·s^{-2} to 0,02 m·s^{-2}.

2.2 Additional metrics

Although the overall VDV, is not proposed in ISO 2631-1, it is useful to evaluate the cumulative VDV due to vibration in all three orthogonal directions. Griffin (1996), provides guidance to calculate the overall VDV as follows:

$$OVDV = \left(k_x^4 VDV_x^4 + k_y^4 VDV_y^4 + k_z^4 VDV_z^4\right)^{\frac{1}{4}} \tag{2.2.1}$$

Where VDV_x, VDV_y and VDV_z are the weighted vibration dose values as calculated by Equation 2.1.7 for the X,Y and Z directions respectively.

2.3 Application of frequency weightings

ISO 2631-1 provides a mathematical definition of the frequency weightings and their respective transfer function parameters in the analogue 's' domain. However it does not provide a method to apply the frequency weightings to acceleration histories discreetly sampled in the time domain.

Frequency weightings can be directly applied in the frequency domain by multiplying the PSD of a time signal by the frequency weighting squared. This procedure yields the weighted frequency content of the acceleration from which the r.m.s. value can be calculated. Some metrics defined in ISO 2631-1, such as crest factor & VDV require the time domain solution. As such they can not be calculated form frequency domain data.

Rimell and Mansfield (2007) describes the implementation of all of the weighting filters defined in ISO 2631-1, and other standards, as digital Infinite Impulse Response (IIR) filters, and provides the necessary formulae to directly calculate the filter coefficients for any sampling frequency. The technique used to obtain the discrete 'z' domain IIR filter coefficients was to apply the bilinear transform to each analogue 's' domain cascade filter as shown below:

$$s \rightarrow 2\left(\frac{1-z^{-1}}{1+z^{-1}}\right) \tag{2.3.1}$$

It must be noted that there is a a non-linear relationship between the analogue frequency and the digital frequency. Pre-warping should be applied to frequencies used in the analogue 's' domain to account for the non-linear relationship (Rimell and Mansfield, 2007). The pre-warped frequencies (w_n') can be obtained by:

$$w_n' \rightarrow 2\left[tan\left(\frac{w_n}{2}\right)\right] \tag{2.3.2}$$

For each of the filters as defined in Equations 2.1.1 to 2.1.4 the bilinear transform is applied by replacing the s as in Equation 2.3.1. Each transformed relation is then re-arranged such that it is in the form:

$$H(z) = \frac{b_0 z^{-2} + b_1 z^{-1} + b_2}{a_0 z^{-2} + a_1 z^{-1} + a_2} \tag{2.3.3}$$

Where b and a are the coefficients for an IIR filter.

By applying the above method to the various cascade filters, the IIR filter coefficients were determined by Rimell and Mansfield (2007) as presented in Table 2.4.

2.4 Further research on frequency weightings

Frequency weightings were initially derived from equivalent-sensation contours obtained on seated subjects (Thuong and Griffin, 2011). ISO 2631-1 specifies the same frequency weightings for the evaluation of the standing posture as for those in a seated posture.

Thuong and Griffin (2011) experimentally investigated the equivalent comfort contours of standing subjects in the vertical and horizontal directions over

Table 2.4: Individual filter co-efficients (Rimell and Mansfield, 2007)

	H_h	H_l
a_0	$4Q_1 + 2w'_1 + w'^2_1 Q^2_1$	$4Q_2 + 2w'_2 + w'^2_2 Q_2$
a_1	$2w'^2_1 - 8Q_1$	$2w'^2_2 Q_2 - 8Q_2$
a_2	$4Q_1 - 2w^1_1 + w^2_1 Q^2_1$	$4Q_2 - 2w'_2 + w'^2_2 Q_2$
b_0	$4Q_1$	$w'^2_2 Q_2$
b_1	$-8Q_1$	$2w'^2_2 Q_2$
b_2	$4Q_1$	$w'^2_2 Q_2$
	H_t	H_s
a_0	$4Q_4 + 2w'_4 + w'^2_4 Q_4$	$\frac{4Q_6+2w'_6+w'^2_6 Q_6}{Q_5}$
a_1	$2w'^2_4 Q_4 - 8Q_4$	$\frac{2w'^2_6 Q_6-8Q_6}{Q_5}$
a_2	$4Q_4 - 2w'_4 + w'^2_4 Q_4$	$\frac{4Q_6-2w'_6+w'^2_6 Q_6}{Q_5}$
b_0	$w'^2_4 Q_4 + 2\frac{Q_4 w'^2_4}{w'_3}$	$\frac{4Q_5+2w'_5+w'^2_5 Q_5}{Q_6}$
b_1	$2w'^2_4 Q_4$	$\frac{2w'^2_5 Q_5-8Q_5}{Q_6}$
b_2	$w'^2_4 Q_4 - 2\frac{Q_4 w'^2_4}{w'_3}$	$\frac{4Q_5-2w'_5+w'^2_5 Q_5}{Q_6}$

the frequency range 0,5 to 16 Hz. Frequency weightings based on these equivalent comfort contours where calculated and then compared to those in ISO 2631-1. It was concluded that the vertical weighting is similar to that of W_b (which is the vertical weighting filter proposed in BS 6841 (1987), and only deviates slightly from W_k below 4 Hz (BS ISO 2631-1, 1997)) however the horizontal (both fore-aft and lateral) weighting (Figure 2.2) are not consistent with that of W_d in ISO 2631-1. The research suggests that the use of W_d as a horizontal weighting filter for the comfort evaluation of standing subjects over-estimates the actual discomfort between 0,5 and 16 Hz.

2.5 Just noticeable difference thresholds

The Just Noticeable Difference (JND) threshold is defined as a minimum change in some aspect of a stimulus that an observer could detect (Matsumoto *et al.*, 2002). The difference in stimuli may be a change in frequency content or amplitude. In this project JND threshold refers to only a change in amplitude. The JND threshold my be expressed as a difference threshold, which is equal to the minimum change in stimuli acceleration magnitude or as a relative difference threshold which is calculated according to Weber's law.

Weber's law states that the ratio of difference threshold to stimulus intensity is constant, as shown by:

$$\frac{\triangle I}{I} = C \tag{2.5.1}$$

Where I is the reference stimulus amplitude, $\triangle I$ is the difference threshold and C is a constant, which is also referred to the relative difference threshold or Weber's ratio.

It is convenient to define the JND in terms of a relative difference threshold as this would allow for it to be applied directly to any vibration amplitude. The JND threshold is an important factor to be considered in the design of machinery and vehicles as it allows the designer to know the minimum change in comfort which the end user would be able to detect. The designers of machinery and vehicles may desire to improve the comfort of the users by reducing the vibration levels or the designer intend for the user to detect faults, such as rotating unbalance or bearing failure, by sensing the increased discomfort.

2.6 Psychophysical methods

The determination of human sensitivity to whole-body vibration is based on the use of various psychophysical measuring methods in the laboratory. These methods have been developed primarily for the psychoacoustic field of study, however are commonly used in JND threshold tests for whole-body vibration.

For all JND test, the subjects are exposed to a set of two stimuli with different vibration amplitudes. This may be in the form of two separate stimuli or in one continuous stimuli with discrete steps in vibration amplitude. The subject is then required to identify a characteristic of one of the vibration amplitudes. For example a subject may be required to identify which of two stimuli is greater, the first or the second. If the subject identifies the greater vibration correctly, it is deemed a positive result, if not it is a negative result.

2.6.1 Methods of stimulus presentation

There are many ways which the stimuli can be presented. The most common are presented in the following list (Gescheider *et al.*, 1990).

- Gated pedestal method: In this method the subject is exposed to two vibratory stimuli of equal time duration, separated by a time interval. The subject is then required to judge which was of a greater amplitude.
- Continuous pedestal method: The subject is exposed to an ongoing vibration stimuli of a given magnitude, with a short duration of increased amplitude. Subjects are required to detect the short period of increased amplitude.
- Two burst continuous pedestal method: The subject presented two successive vibration stimuli, one of which contains a short duration of increased amplitude. The subject is then required to identify which one contains the short duration of increased amplitude.

Gescheider *et al.* (1990) investigated the differences in JND threshold estimates as determined by different methods of stimuli presentation. The input stimulus was delivered through a contactor to the thenar eminence (palm of hand). The durations for the test where as follows: In the gated pedestal tests, two 700 ms bursts separated by a 1000 ms pause. In the continuous pedistal tests a 700 ms increase in amplitude was introduced to a continuous stimuli. In the two burst continuous pedestal tests, two 1500 ms stimuli where presented, one containing a increase in amplitude for 500 ms. The results (Figure 2.3) show that the thresholds determined by the continuous pedestal method of stimulus presentation where consistently lower for detecting increments in amplitude than in the gated or two burst pedestal methods [Gescheider *et al.* (1990)].

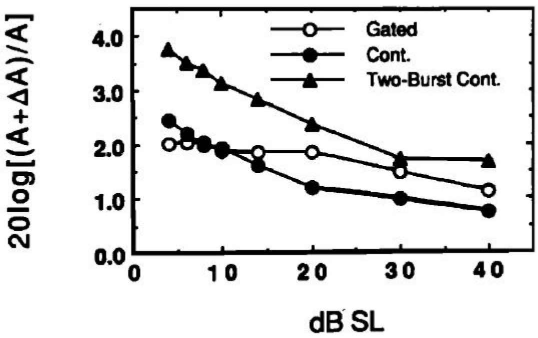


Figure 2.3: Difference Thresholds at a range of magnitudes for different methods. A: amplitude of weaker vibration; △A:smallest perceptible increment in magnitude. [Gescheider *et al.* (1990)]

2.6.2 Psychophysical testing methods

There are many psychophysical testing methods that can be used. The relevant methods that are used for JND threshold investigations are provided in the following list.

- Method of limits: A set of stimuli (reference and alternative stimuli) of noticeably different amplitudes are presented to a s subject. The subject is required to identify one of the vibration amplitudes. If a positive response is obtained then the alternative stimuli amplitude is reduced and the test repeated. The test is continued in this manner until negative result is obtained. The difference threshold is calculated by taking average of the last two alternative stimuli amplitudes and subtracting the reference amplitude. This produce a difference threshold estimate for a 50% chance of a correct response.

- The transformed up down procedure: This method was proposed in Levitt (1971) and is also referred to as the up-down transformed response (UDTR) procedure. The method includes exposing a subject to a set of stimuli, one reference and one alternative. The subject is then asked to identify one of the vibration amplitudes. If the subject response is positive n times in a row then the alternative amplitude is decreased. If the subject response is negative then the amplitude is increased. This process is repeated until m reversals have been completed. A reversal begins with a set of n positive responses in a row and ends with a negative response. The difference threshold for each reversal is calculated from average of the alternative stimuli amplitude of the first set of positive responses in the reversal and the amplitude of the negative response, subtracted from the reference stimuli amplitude. With $n = 2$ a JND threshold is obtained with 70,7% chance of a correct response.

JND thresholds determined using the UDTR procedure with $n > 1$ are expected to produce larger JND thresholds than the method of limits due to the higher chance of correct response (Matsumoto *et al.*, 2002).

2.7 Previous whole-body vibration JND Studies

Many studies have been conducted to investigate the JND threshold for the whole-body vibration of seated subjects. Table 2.5 provides details of the relevant studies. Figure 2.4 shows the results from the JND studies using single frequency sinusoidal stimuli. The differences in JND thresholds obtained from the different studies can be attributed to the different stimulus presentation types used, differences in subject groups, the duration of vibration exposure per trial and the psychophysical testing method used (Matsumoto *et al.*, 2002). To the best of the author's knowledge no literature exists with respect to the whole-body vibration JND levels on standing subjects.

2.8 Previous vibration studies on ships

To the best of the author's knowledge, only few published articles exist, with respect to vibration measurement results aboard ships other than the S.A. Agulhas II. None of the studies were reported in terms of whole-body vibration, nor included measurements of slamming.

Belov and Spiridonov (2012) investigated the vibration levels aboard the icebreakers Sankt-Peterburg and Arktika and the ice capable transport ship Vitus Bering. The purpose of the investigation was to assess the vibration damping characteristics of ice when sailing through ice. It was found that

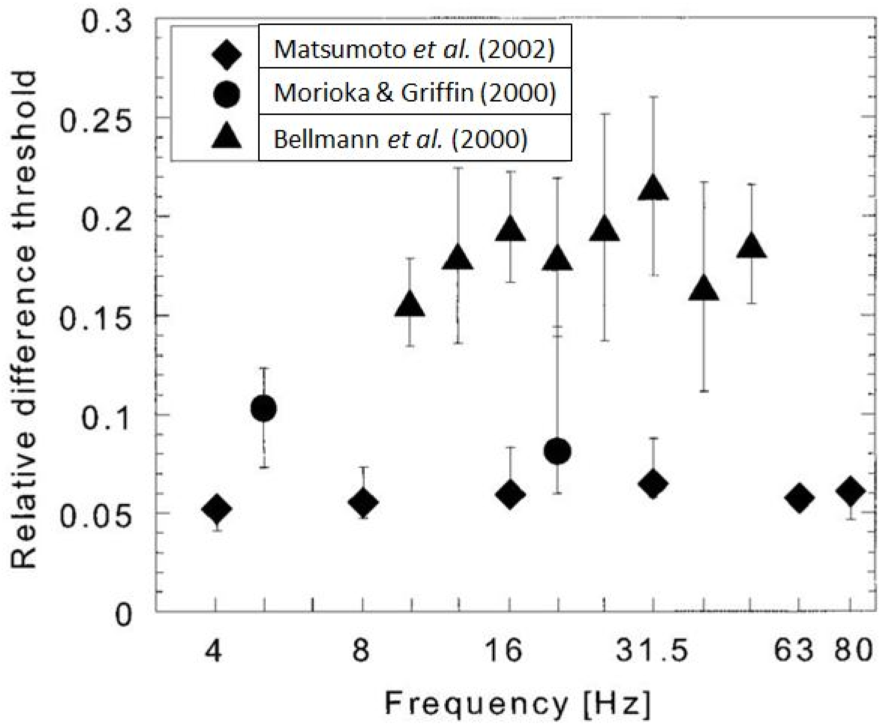


Figure 2.4: Comparison of results from studies investigating whole-body vibration JND threasholds of sinusoidal stimuli over a range of frequencies (Matsumoto *et al.*, 2002). The reference stimuli levels for Matsumoto *et al.* (2002), Morioka and Griffin (2000) and Bellmann (2002) where 0,7 m·s^{-2}, 0,5 m·s^{-2} and 0,063 m·s^{-2} respectively

although the ice did have a significant damping effect, the overall vibration levels where greater in ice due to hull and propeller interactions with the ice.

2.9 Previous whole-body vibration studies aboard the S.A. Agulhas II

Three studies have been conducted regarding whole-body vibration aboard the S.A. Agulhas II. Bekker (2013*b*) investigated the levels of vibration exposure of the vessel during ice-trials in the Bay of Bothnia. The measurements where preformed for a seated subject on the Cleeman Dolphin Seat on the Bridge of the vessel. The results of the study showed that the crest factor did not exceed 4,4 thus according to ISO 2631-1 the r.m.s. metric is appropriate for the evaluation of the measured accelerations. Vibration levels during the ice trials where up to 4,5 times that in calm open seas.

Soal and Bekker (2013) analysed the whole-body vibration during the 2012-2013 Antarctic voyage for a standing person in the Bridge. The analysis was conducted for specific case studies including pack ice, carving, ramming, engines only, open seas - rough weather and open water - calm weather. The measurement was not continuous and thus the comfort for the duration of the voyage could not be analysed. The study did not include an investigation into slamming.

Bekker (2013*a*) conducted a study to investigate vibration levels when waves slam the aft deck of the vessel. This study was motivated by complaints from the captain and crew of the vessel to disconcerting vibration experiences, caused by slamming, during the 2013 Marion voyage. The results where compared to the DNV comfort class. As such the vibration levels where not human weighted and thus can not be compared to whole-body vibration studies.

2.10 Conclusions from the literature survey

ISO 2631-1 provides the relevant frequency weightings and metrics for the evaluation of whole-body vibration of standing posture. A technique to apply the frequency weightings to accelerations measured in the time domain is provided by Rimell and Mansfield (2007).

Whole-body vibration has been assessed for specific case studies, however no continuous comfort measurements have been conducted aboard the S.A. Agulhas II. Vibrations due to slamming have been investigated but the investigation did not asses the whole-body vibration comfort associated with the vibrations. As such this project seeks to determine the whole-body vibration comfort aboard S.A. Agulhas II while waves are slamming the aft of the ship.

Various psychophysical methods can be used to determine a JND threshold, however the outcome of which may be affected by the selection of method. JND thresholds have been determined for a range of single frequency and automotive stimuli for seated subjects, while, to the best of the author's knowledge, no JND studies have been conducted on standing subjects. As such, this study aims to evaluate the JND thresholds for standing subjects with both real world and sinusoidal vibration, and compare the results with those found in literature for seated subjects.

Table 2.5: Summary of previous whole-body vibration JND experiments

Authors	Method of testing		Time (s)			Stimulus	Seating properties	
	Presentation method	Psychophysical method	Exposure	Ramp up-down	Pause		Backrest	Footrest
Matsumoto *et al.* (2002)	Gated	Method of limits	4	0.5	2	Sine	No	Stationary
Mansfield and Griffin (2000)	Gated	UDTR	10	0	2	Automotive	Yes, 23°	Vibrating
Morioka and Griffin (2000)	Gated	UDTR	4	0	1	Sine	No	Stationary
Bellmann (2002) <=12,5 Hz	Continuous	UDTR	2	0	0	Sine	Yes	Vibrating
Bellmann (2002) >12,5 Hz	Continuous	UDTR	1	0	0	Sine	Yes	Vibrating

Chapter 3

Experimental setup

The scientific contribution of this work proposes to establish whole-body vibration levels on-board an ice-going vessel in open water and in ice as well as to determine the JND threshold for a vibration as experienced on such a vessel. To this end the vibration was measured aboard the S.A. Agulhas II during the 2013-2014 Antarctic voyage and vibration recoded during the voyage was re-created in a laboratory environment on a man-rated shaker platform, such that JND threshold for such a vessel can be investigated.

3.1 Whole-body vibration measurement aboard the S.A.Agulhas II

A whole-body vibration measurement was conducted during the 78 day 2013-2014 Antarctic voyage between Cape Town, Antarctica and the South Sandwich Islands.

3.1.1 Voyage details

The measurement included sailing in a variety open water and ice conditions. Swell heights from 0 to 8 meters where recorded in open waters, while in ice, ice thickness's of up to 3 meters thick where encountered. Figure 3.2 shows a map of the voyage while Table 3.1 provides the details of each leg of the journey. The GPS co-ordinates for the map were extracted from the Scientific Data System (SDS).

Figure 3.3 provides the swell heights and average ice thickness for the duration of the voyage. The swell hight was visually estimated by the navigational officers on the Bridge every four hours and recorded in the vessel's log book. The ice thickness was estimated from visual observations made in the Bridge by the members of the Sound and Vibration Research Group and consortium partners. Since the ice thickness varies rapidly as the ship sails through the ice and is difficult to measure with more than twenty centimetre precision, the thickness estimation was made every ten minutes, with the thickness being recorded into categories of: 0 to 20 centimetres, 20 to 40 centimetres, 40 to 60 centimetres, 60 to 80 centimetres, 80 to 100 centimetres, 100 to 120 centimetres, 120 to 140 centimetres, 140 to 160 centimetres, 160 to 180 centimetres, 180 to 200 centimetres, 200 to 250 centimetres, 250 to 300 centimetres, greater than 300 centimetres. The ice thickness was estimated by entering how many minutes of each ice condition were experienced in a ten minute period. The average ice thickness was then calculated from the data by averaging the minutes in each respective category over a ten minute period.

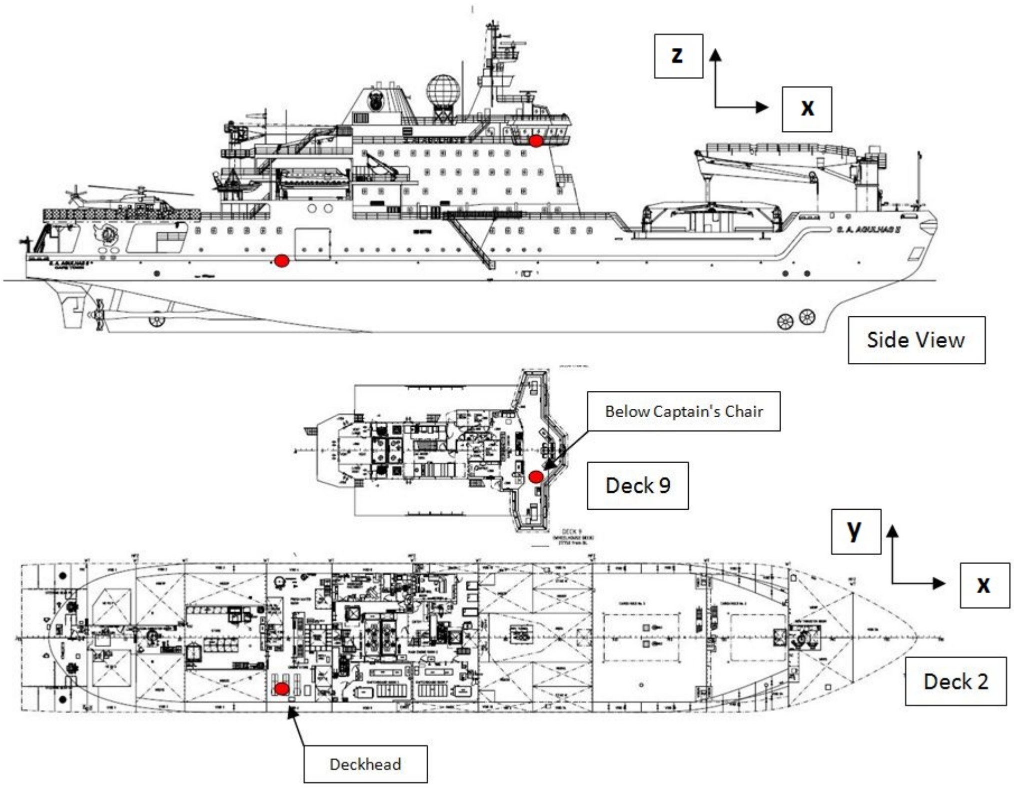


Figure 3.1: Placement of accelerometers in the Bridge and in the Operations Room

Table 3.1: Voyage Details

From	To	Description
1	2	The ship departed from Cape Town Harbour on 28 November to Akta Bukta. The course sailed included a stretch down the Greenwich meridian to preform oceanographic operations. The measurement was initiated on 3 December.
2	3	Ice was first encountered on 7 December. As the ship progressed, the ice gradually became thicker and more densely distributed. On 9 December the ice became too thick to break through. Ramming techniques where used to progress through the ice. The ship routinely became beset in ice, unable to go astern for periods up to 2 hours until the ship broke loose. During these periods blocks of ice where sucked through the propellers causing high vibration levels as the ice was milled. On the 22 December the ship pushed up against the ice shelf after 3 hours of carving the ice surrounding the offloading point at Akta Bukta.
3	4	The ship remained pushing up against the shelf to offload crew and passengers until 24 December when it departed for Penguin Bukta. The voyage was mostly along open seas in the shore lead and little ice was encountered. On 25 December the ship reached Penguin Bukta.
4	5	The ship departed from Penguin Bukta on 30 December, sailing for Southern Thule.
5	6	Calm open seas where encountered on 1 January. Southern Thule was reached on 4 January.
6	7	The ship set sail for South Georgia on 4 January and arrived there on 6 January.
7	8	The vessel departed for Penguin Bukta on 6 January. The route sailed was not direct as the ship was required to sail a zigzag pattern near the ice edge for whale watching research.
8	9	On 23 January, after the whale watching research was complete, the ship entered the ice. Penguin Bukta was reached on 24 January. The ship pushed up against an ice flow and remained there for helicopter operations.
9	10	The ship remained at Penguin Bukta until 26 January when she departed for Akta Bukta. Atka Bukta was reached on 27 January and began carving bay ice to open up the bay. The ship completed carving on 28 January and pushed up against the ice shelf at Atka Bukta.
10	11	The ship set sail from Akta Bukta on 31 January and set sail for South Africa.
11	12	Open seas where encountered on 1 February. The ship continued sailing for South Africa, arriving at Saint Helena Bay on 12 February where the ship spent the day slowly sailing around the bay before setting sail for Cape Town Harbour. The measurement was turned off on 12 February. The ship came into the harbour and moored on 13 February.

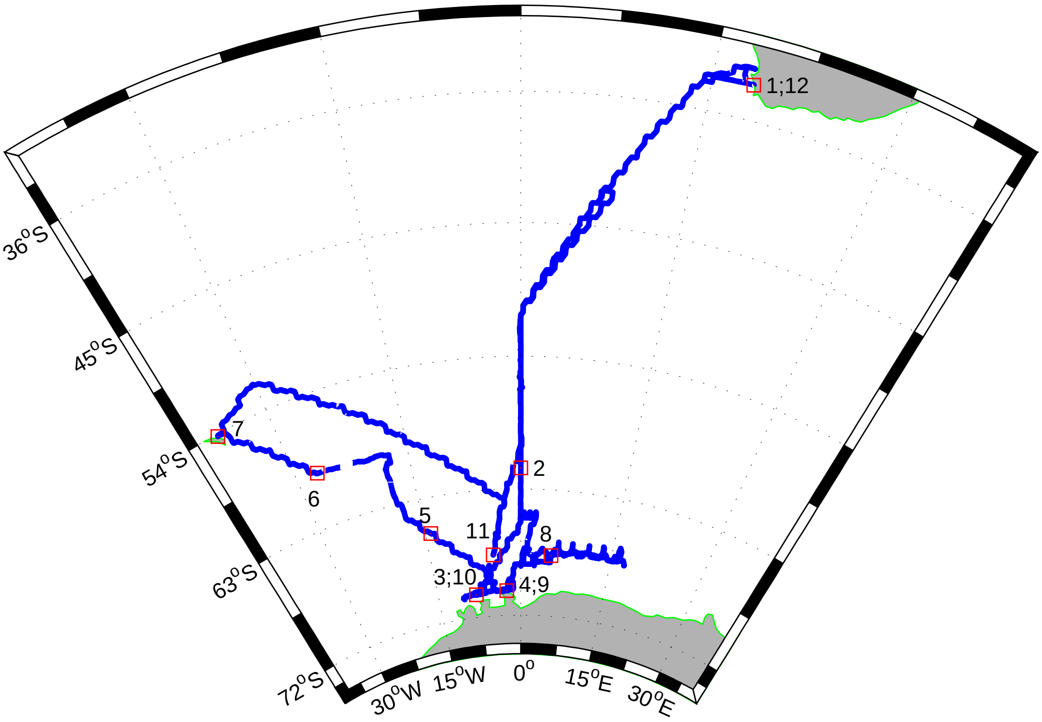


Figure 3.2: Map of the 2013-2014 Antarctic voyage: 1 & 12: Cape Town Harbour; 2: Start of ice; 3 & 10: Akta Bukta; 4 & 9: Penguin Bukta; 5: End of ice; 6: Southern Thule; 7: South Georgia; 8: Start of ice; 11: End of ice

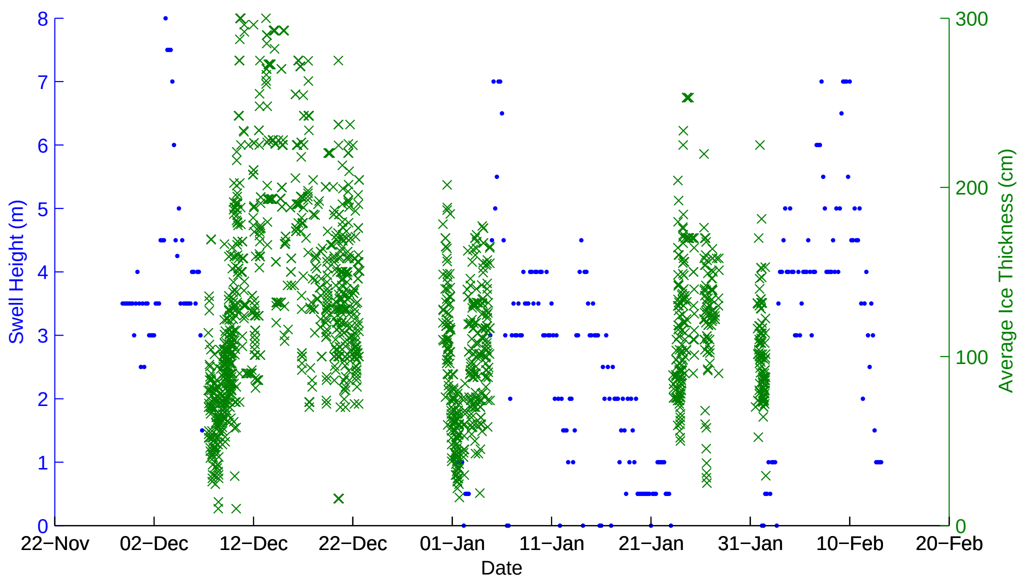


Figure 3.3: Sailing conditions: •: Swell height; × Average ice thickness

3.1.2 Measurement setup aboard the S.A.Agulhas II

The two measurement locations, including the Bridge and Operations Room, are as shown in Figure 3.1. A tri-axial accelerometer was secured with super glue to a transverse beam on the deckhead (ceiling of the deck) of deck 2, directly below the Operations Room (deck 3). The measurement location was chosen because the Operations Room is used by many scientist, including oceanographers and marine biologists, as work place, and thus the comfort of such an area is of interest.

A set of three seismic accelerometers where secured to an aluminium mounting block via stud mounts and the mounting block was secured directly below the captains chair, on the junction of a transverse and a girder, in the Bridge using super glue (Figure 3.4). This is the same measurement position as was used in the previous vibration studies, thus allowing for the results to be compared.

Figure 3.4: Seismic accelerometer mounting

The axis of the accelerometers in both measurement locations where lined up to the co-ordinate system shown in Figure 3.1, hereby assuming a forward-facing subject. It must be noted that although the people in the Bridge or Operations Room may not always be forward-facing, the analysis of the whole-body vibration level would not be effected as the weighting filter (W_d) is the same for both the x and y directions. Further specifications of the accelerometers used are provided in Table 3.2.

A LMS SCADAS mobile data acquisition unit with a V8 module was used to record the electrical signals from the accelerometers. LMS Test.Lab Turbine Testing was utilized as a software interface since it provided for “near” continuous measurement of the 78 day voyage. In fact, a total of 64 days worth of data was recorded as technical difficulties hindered the continuous operation of the measurement setup. The LMS hardware was placed on the second deck near the Operations Room accelerometer. A sample rate of 2048 Hz was chosen as it was above the minimum sample rate to meet the requirement of the digital filter which is specified for human weighting of signals in the time domain, as specified in ISO 8041 and BS 6841 with a value of 900 Hz (Rimell and Mansfield, 2007).

Table 3.2: Details of accelerometers used during the measurement aboard the S.A. Agulhas II

Description	Model number	Serial number	Sensitivity ($V/m/s^2$)	Direction
Seismic	393B12	23820	1,098	x
Seismic	393B12	12298	1,088	y
Seismic	393B12	12299	1,074	z
Tri-axial	356B40	26977	10,52	x
Tri-axial	356B40	26977	10,64	y
Tri-axial	356B40	26977	10,55	z

3.2 The dynamic seat testing facility (DSTF)

The DSTF is a man-rated vertical shaker used for investigations with respect to human comfort. It is situated in the Structural Laboratory of the Department of Mechanical and Mechatronic Engineering at Stellenbosch University. Details of the DSTF as well as the various equipment required to control the DSTF are provided in this section.

3.2.1 Components of the DSTF

The DSTF (Figure 3.5) is a man-rated shaker platform that comprises of a 100 kN servo-hydraulic test actuator that is coupled to a rigid aluminium platform. The platform is coupled via a set of linear bearings to a vertical guide thus restraining the platform to vertical motion. The specifications of the actuator are as provided in Table 3.3

The servo valve that controls the actuator is controlled by a MTS 407 controller which facilitates closed loop PID displacement control of the platform. The feedback for the position is provided by a linear variable displacement transducer (LVDT) which is mounted inside the actuator. The controller has a built in function generator that can generate sinusoidal, triangular and square wave forms. The setpoint (desired value of the measured process output (Bequette, 2003). In the case of the DSTF the measured process output it is the displacement of the platform) for the PID algorithm can be selected from either the function generator or an external input. For external inputs the

Table 3.3: Actuator specifications

Description	Specifications
Static force rating	100 kN
Dynamic force rating	75 kN
Stroke	200 mm (± 100 mm)
Frequency range	0 - 25 Hz
Maximum velocity	0,4 - 0,5 m/s
Bearings	Sealed, Hydro-dynamic
Supply pressure	280 Bar

voltage supplied must be between -10 V and 10 V where a voltage of 10 V is associated with a displacement of 125 mm.

A set of bump stops positioned at ±125 mm ensure that the platform will remain within the actuator limits. This prevents damage to the actuator in the event of valve or control failure. Safety switches are positioned at +100 mm and −100 mm from the centred actuator position. This allow the controller to detect if the position of the actuator is not within limits. In this case the hydraulic pressure will be switched off. This safety feature ensures that the displacement will remain within safe limits, even if the LDVT fails. A software limit (at ±50 mm), which if tripped turns off the hydraulic pressure, is implemented in the controller as a primary precaution to prevent the over displacement of the actuator.

An emergency stop button is placed on the controller and is easily accessible to the operator, while another is placed on a pole next to the platform and is easily accessible to the subject. If pressed these buttons turn the hydraulic pressure off.

A hand rail is mounted on the DSTF to ensure that if the subject loses their balance they can use the hand rail to stabilise themselves. A cage is securely mounted around the DSTF to restrict access to the moving parts of the system.

3.2.2 Acceleration measurement

A capacitive DC accelerometer was secured to the top of the DSTF platform directly above the actuator coupling. The accelerometer was connected to a capacitive accelerometer signal conditioner. The specifications of the accelerometer and signal conditioner are provided in Table: 3.4

3.2.3 Data acquisition and signal generation

As mentioned in section 3.2 the DSTF controller can take a voltage input which controls the setpoint. The National Instruments CompactDAQ chassis (NIcDAQ) with a NI 9263 analog output module and a NI 9234 analog input

Table 3.4: Acceleration measurement specifications

Manufacturer	Type	Model no.	Sensitivity [mv/(m/s^2)]
PCB Electronics	DC accelerometer	LW6304	20.22
PCB Electronics	Signal Conditioner	445A101	-

module where used to provide the setpoint voltage for the DSTF and measure the voltage from an accelerometer. Details of the above components are provided in Table 3.5

Table 3.5: Data acquisition and signal generation hardware specifications

Manufacturer	Type	Model no.	Resolution [bits]
National Instruments	Chassis	NIcDAQ 9184	-
National Instruments	Analog input	NI 9234	24
National Instruments	Analog output	NI 9263	16

The analog input module has a built in anti-aliasing filter. The alias-free bandwidth of the signal is $0.45 \cdot fs$. The sample frequency was chosen as 2048 Hz such that it was the same as used for the ship vibration measurement.

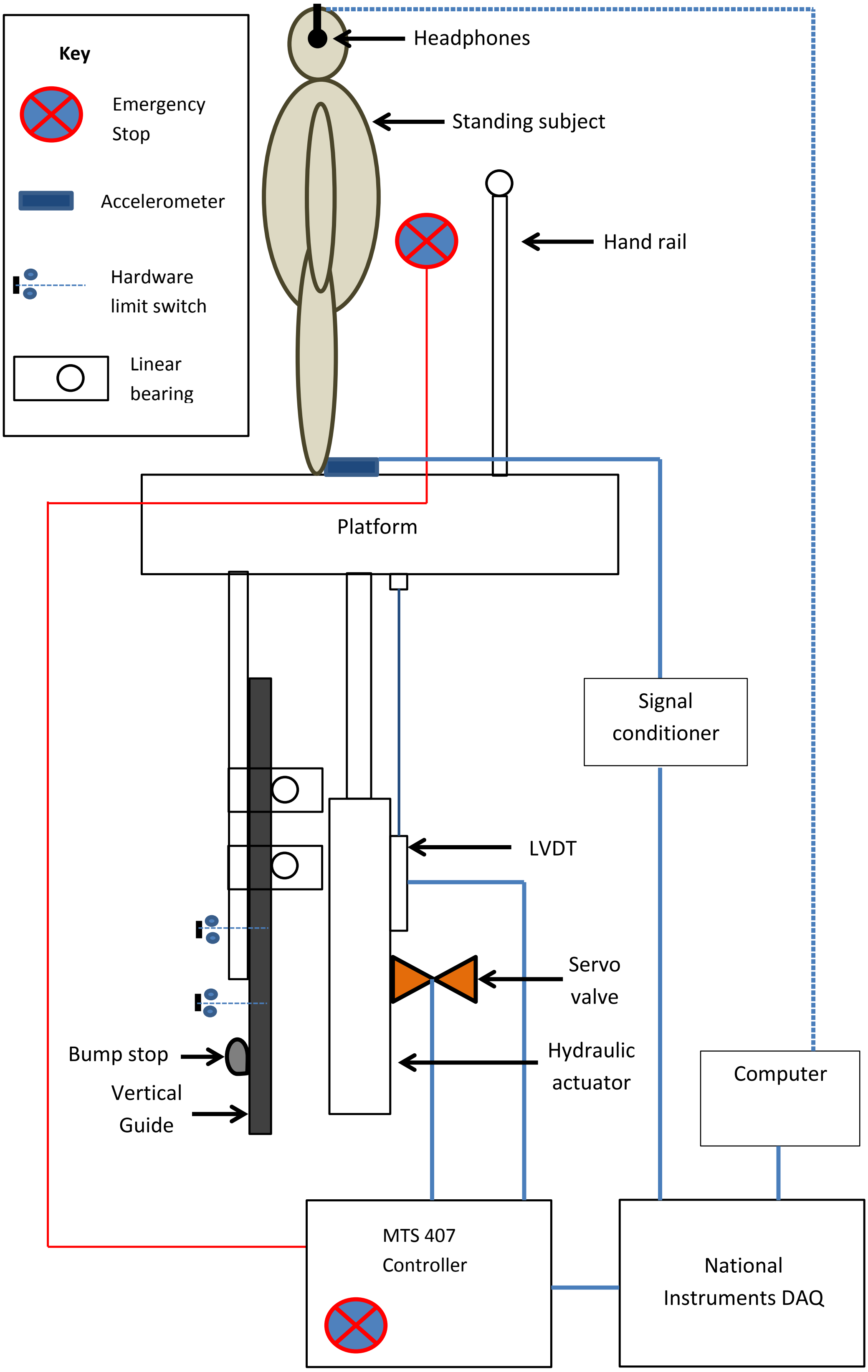


Figure 3.5: Diagram of the Dynamic Seat Testing Facility (DSTF)

3.2.4 Characterisation of the DSTF

The DSTF is provided an input voltage to specify the setpoint. The PID controller then varies the valve to achieve the setpoint. Feedback from the LDVT provides information on the position of the platform to the PID controller. The P, I and D values, which can be changed on the controller, have a direct impact on the performance of the DSTF, for example a large P value will make the DSTF more responsive and may cause overshoot, while a small P value will cause the DSTF to be less responsive.

The seat testing facility file of accompaniment provides the control parameters to be used for the DSTF. It states that the PID values should be as follows: $P = 12$ V/V; $I = 8$ rps; $D = 0$ s. Using these control parameters the DSTF had major problem in that it became extremely unstable. For a given step input, the platform would overshoot the desired value, and oscillate about that that setpoint, at a frequency of between 30,5 and 33 Hz (depending on the dynamic loading of the platform) with an unweighted amplitude of up to 8 m$\cdot$s^{-2} r.m.s. This behaviour did not only occur with a step input, but also when playing white-noise with a frequency content of between 1 and 25 Hz or a pure sinusoidal signal.

The instability was removed by lowering the P value and turning off the I control. After extensive testing a P value of 4,67 V/V was decided on as it provided negligible overshoot in a step response test while still being adequately responsive. The PID parameters could be better selected by using a standardised procedure, as provided by (Cooper *et al.*, 2006) to further optimise the PID control such that the response of the system is improved. This was however not completed in the duration of the project and is thus a suggestion for future work. With the new PID control parameters as chosen earlier, the transmissibility of the DSTF is as shown in Figure 3.6.

It must be noted that the transmissibility estimates shown in Figure 3.6 where calculated using the technique provided in Section 4.3.2. As such the the frequency content of the signal input to the DSTF is limited between 1 and 25 Hz, which implies that the transmissibility estimate will only be relevant between 1 and 25 Hz.

Since the transmissibility estimate varies greatly from the ideal value of one, the profiles sent to the DSTF for vibration reconstruction must first undergo a calibration procedure to obtain the desired output accelerations. Details of the calibration procedure are provided in Section 4.3.

A further problem with the DSTF is that it creates undesirable frequency content. This is shown in Figure 3.7 for a pure sinusoidal input over a range of frequencies. There appears to be an impulse as the cylinder changes direction. This impulse then causes vibration which slowly damps out, until the cylinder changes direction again. This problem was given the name ‘clicking’.

Further testing was conducted to investigate the possible cause of the problem. The valve command and LDVT signals were sent to an oscilloscope, al-

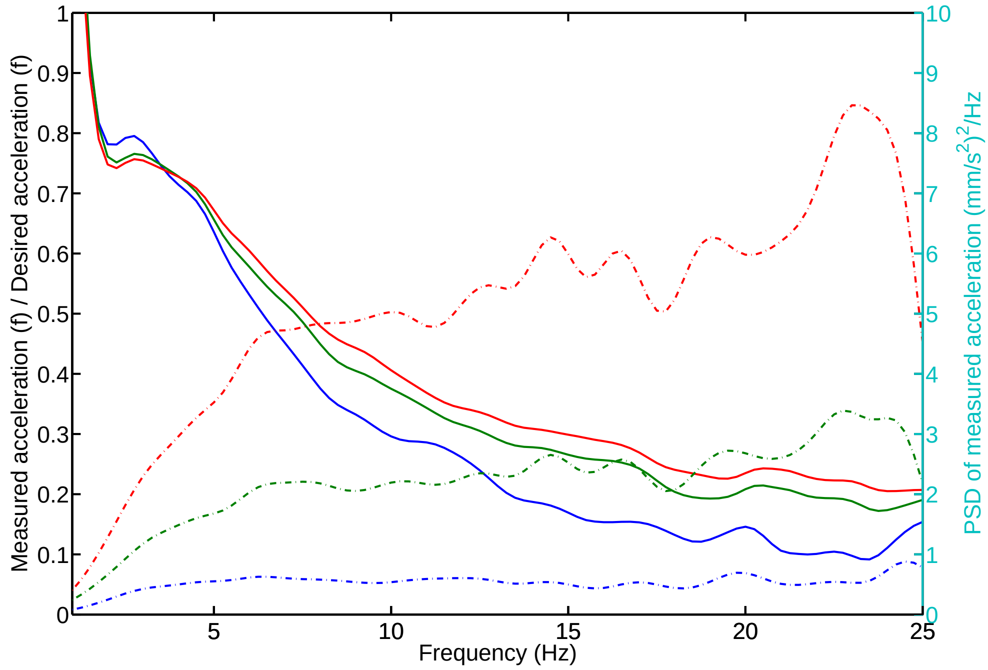


Figure 3.6: Transmissibility of the DSTF at three different amplitudes. Test conducted using white noise as an input, with a 67 kg female subject standing on the platform. –: Transmissibility estimate; -·-: PSD of measured output

lowing for the investigator to monitor the performance of the controller. It was noted that the valve command signal did not include any undesired frequency content, thus it was concluded that the problem was not caused by the controller.

It was suspected that the problem was caused by the piston rod having come loose from the piston. This was a logical explanation as the clicking occurred only when the piston changed direction. The hydraulic actuator was removed and sent to a specialist company for repairs. When the cylinder was opened, the piston and piston rod where firmly connected, and thus possibility of the piston rod being loose was eliminated. The seals inside the hydraulic actuator where replaced and the unit re-installed into the DSTF.

Upon re-testing the DSTF, it was noted that the problem persisted. Since it is known that the hydraulic actuator is in good condition and the controller is not the problem, the problem is suspected to be due to wear on the valve. Unfortunately replacing or repairing the valve was not a financially viable option during the duration of this project. It was decided that work can continue provided that the precise vibration response on the platform is known.

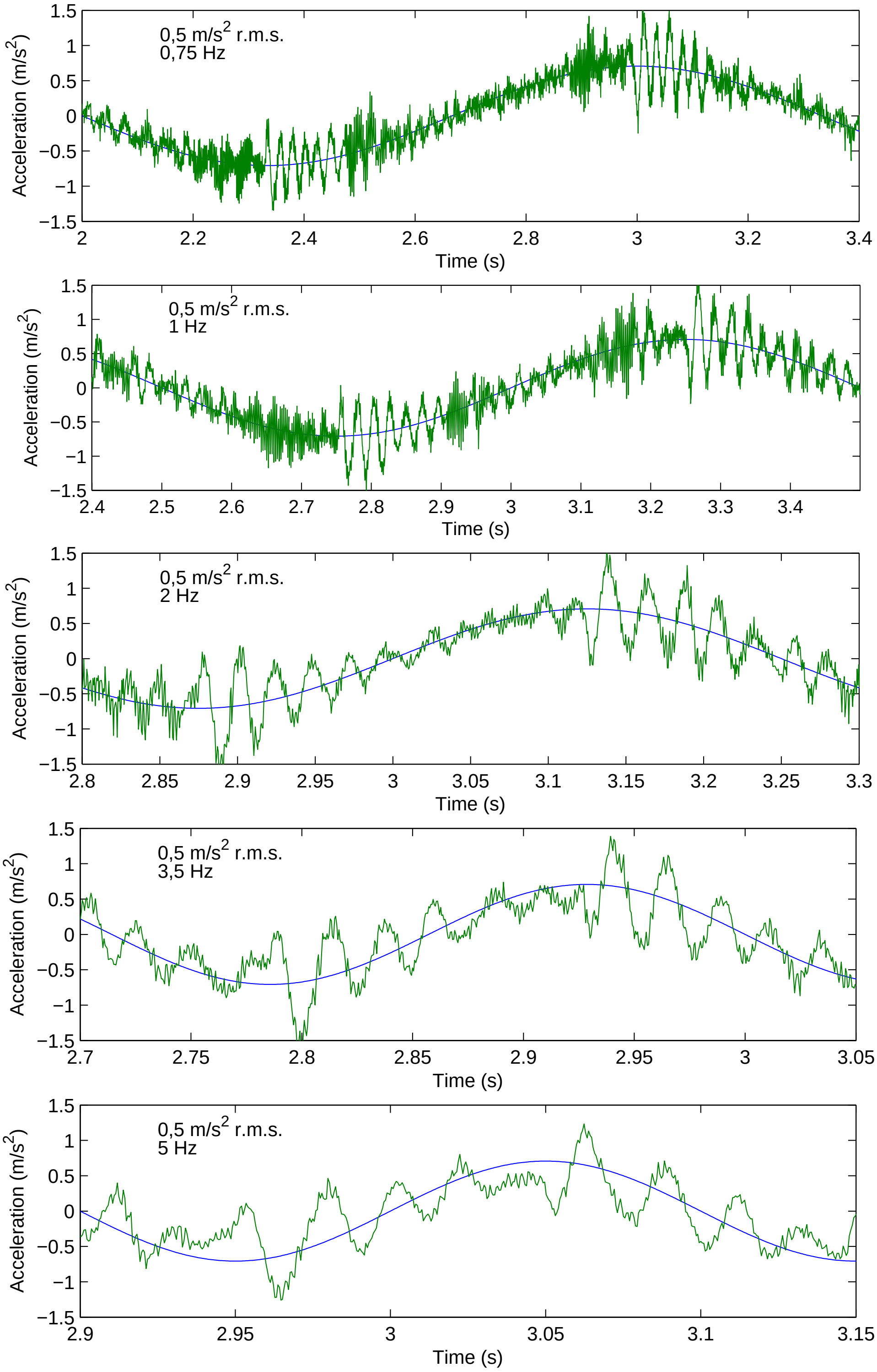


Figure 3.7: Response of the DSTF to a pure sinusoidal input: —: Desired acceleration; —: Measured acceleration

Chapter 4

Experimental method

The determination of just noticeable difference thresholds for vertical vibration requires the participation of human subjects. The average responses of these subjects are used to indicate the change in level of a vibration stimulus that would be just noticeable to a population exposed to such a vibration.

4.1 Subject preparation

It is important that the subjects used to evaluate the JND threshold are prepared for the JND tests. The preparations include filling in and signing various safety forms, measuring the weight and height of the subjects, informing the subjects of the safety instructions and providing them with general instructions regarding the JND testing procedure.

The subjects where made to understand that their participation in these experiments is consensual and that they are able to terminate their participation at any time of their choosing.

4.1.1 Subject details

The JND tests were conducted on nine subjects including three females and six males. The test subjects where selected such that they covered the range of statures found in the general population. Table: A.1 provides a picture of each subject standing on the platform of the DSTF prior to the start of the testing procedure. Table: 4.1 provides the physical details of each subject.

The subjects where aged between 20 and 25 (mean 22,8) years with an average stature of 1,76 m and an average weight of 74,8 kg. It was ensured that the subjects included a fifth percentile female (Subject 8) and a ninety fifth percentile male (Subject 6) such that the subjects more accurately reflect the general population. All the subjects where free of injury and history of relevant medical condition.

Table 4.1: Details of subjects

Subject	Gender	Age	Weight (kg)	Stature (m)
1	Male	22	73	1,82
2	Male	24	79,5	1,76
3	Male	25	73	1,78
4	Male	22	70,5	1,74
5	Male	20	77,5	1,85
6	Male	24	103	1,86
7	Female	21	85	1,73
8	Female	24	45	1,57
9	Female	23	67	1,76

4.1.2 Safety forms

Prior to testing, the subjects where required to sign the 'Consent form for participation in human vibration testing / demonstration ' (Figure C.1) as well as the 'Medical declaration for the participation of whole-body vibration testing / experiment' (Figure C.2). The operator checked through the medical declaration to ensure that the subject was not injured and did not have a relevant medical condition that could be effected by whole-body vibration. Once each test was completed the subject was required to fill in the 'Record of reactions to mechanical vibration test' (Figure C.3), and the operator filled in the 'Record of subject exposure to mechanical vibration' (Figure C.4). At the end of each set of testing, a plot with all the human weighted r.m.s. exposures was printed for each subject and stored with the safety forms.

4.1.3 General JND testing instructions

The subjects given the following verbal instructions.

- Remove shoes and ensure that you only have a thin pair of socks on.
- Walk up the stairs, holding the hand rail.
- Stand on the platform, ensuring that the accelerometer is not touched.
- Place your feet on the platform such that the back of your heels are touching the line.
- Keep your back straight and relax your hands on your thighs.
- Remain in this position until you are told that you can relax, unless an emergency arises.
- During the JND threshold tests you will be required to wear a headset.

- The test can be aborted at any stage, by simply pressing the emergency stop button.

4.2 Frequency weighting

The calculation of the crest factor and VDV require the weighted acceleration time history. As such, a MATLAB function, FrequencyWeightingTimeDomain.m (Appendix B.1), was created to implement the method provided by Rimell and Mansfield (2007), discussed in Section 2.3. The response of the implemented filters (tested using white noise) in comparison to the filters specified in ISO 2631-1 is presented in Figure 4.1. The response of the implemented filters accurately fit the weighting curves specified in ISO 2631-1.

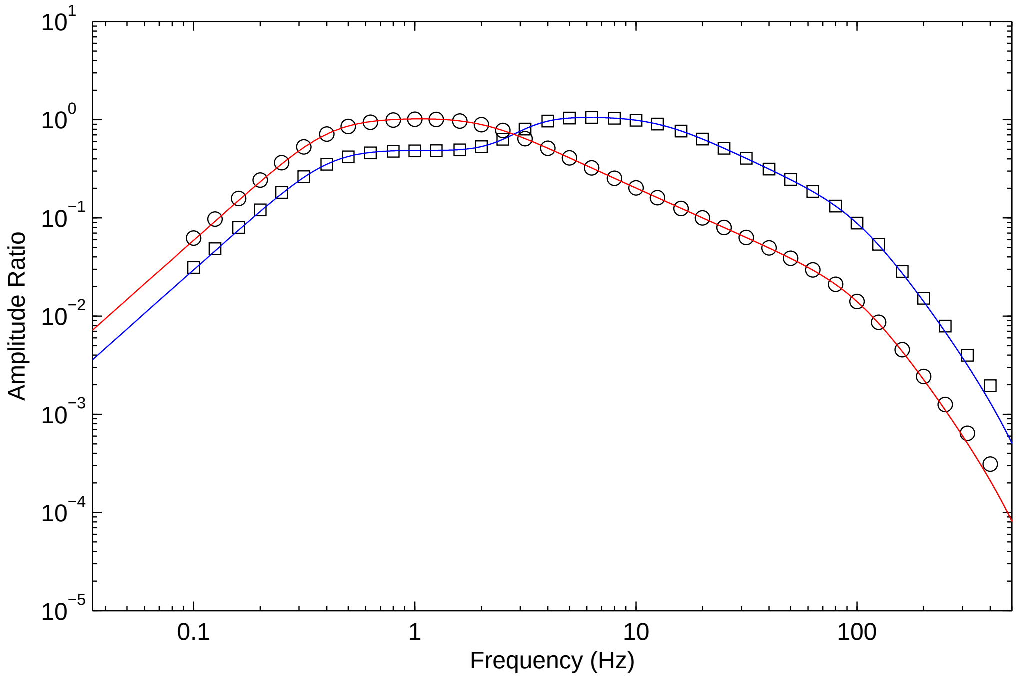


Figure 4.1: Comparison of the frequency weightings proposed in ISO 2631-1 and the implemented filter: ○: ISO 2631-1 W_d (horizontal) weighting filter; □: ISO 2631-1 W_k (vertical) weighting filter; — : W_k (vertical) filter as implemented; — : W_d (horizontal) filter as implemented

4.3 JND stimuli preparation procedure

As shown in Section 3.2.4 the response of the platform to a given input is nonlinear, and also varies with subject. For this reason a calibration procedure was required to ensure the accurate reconstruction of each stimulus. An overview of the stimuli preparation procedure is provided in Figure 4.2.

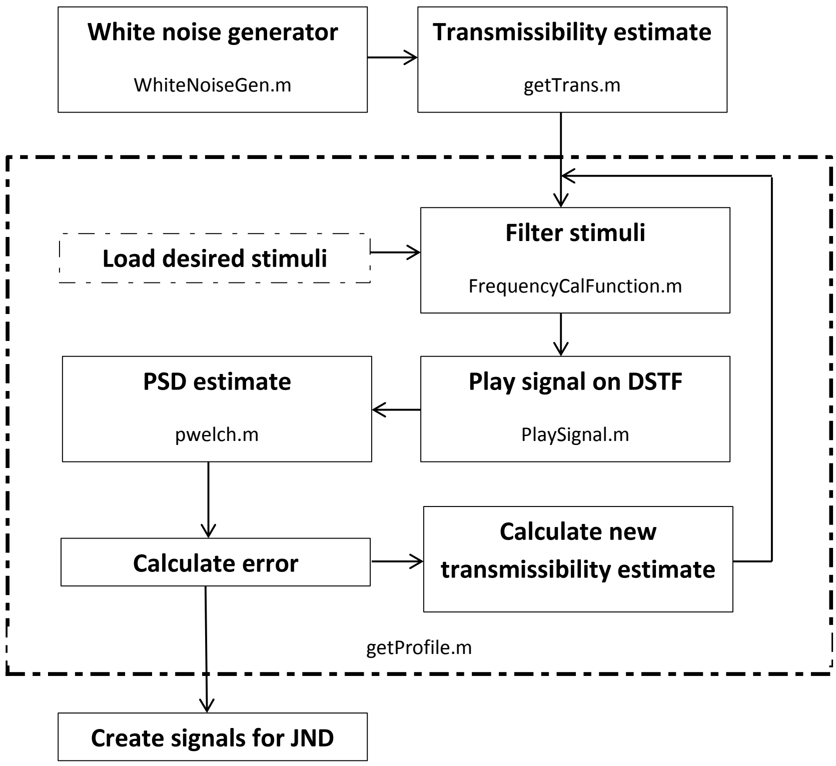


Figure 4.2: Overview of stimuli preparation

4.3.1 White noise generator

The white noise generator (Appendix B.2) produces a random signal such that the frequency content exists in a frequency band between a specified low and high frequency. This is achieved by applying the inverse Fourier transform to a pre-specified frequency content (Figure 4.3) with a randomised phase. The shape of the frequency input was decided on due to it providing more excitation at the higher frequencies where the transmissibility is expected to be lower.

4.3.2 Transmissibility estimate

The `getTrans.m` (Appendix B.3) function uses a set of six white noise signals and multiplied them by three different magnitudes. The eighteen signals are then played to the DSTF via the `PlaySignal.m` function. The PSD estimates of both the input signal and recorded acceleration time history are then calculated using the `pwelch.m` function in MATLAB.

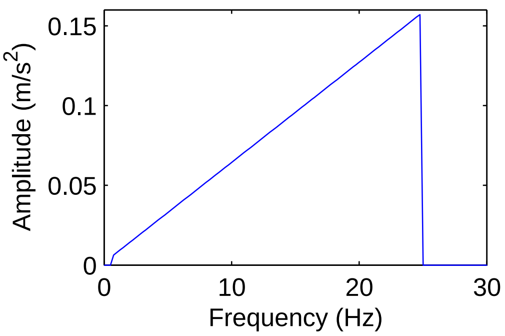


Figure 4.3: Frequency content of the signal returned from the white noise generator, with a specified minimum and maximum frequency of 1 and 25 Hz respectively

Transmissibility estimates of the expected acceleration output for a given displacement input are then calculated as shown in Equation 4.3.1.

$$H_{est}(w) = \frac{PSD_{acceleration}(w)}{PSD_{signal}(w)} \tag{4.3.1}$$

where $PSD_{acceleration}$ and PSD_{signal} are the PSD estimates of each acceleration and signal respectively, as a function of frequency, w (rad/s).

The six transmissibility estimates and acceleration PSD estimates for all three magnitude where averaged and outputted. An example of a transmissibility estimate determined for the DSTF using this algorithm is provided in Figure 3.6.

4.3.3 Filter stimuli

The `FrequencyCalFunction.m` (Appendix B.4) function converts the desired acceleration signal into the frequency domain via a fast Fourier transform and multiplies inverse of the transmissibility estimate to the desired acceleration signal in the frequency domain, as shown below:

$$S_{calibrated}(w) = \frac{S_{desired}(w)}{H_{est}(w)} \tag{4.3.2}$$

where $S_{calibrated}$ and $S_{desired}$ are the fast Fourier transform of the calibrated and desired acceleration signals respectively, as a function of frequency, w (rad/s). Frequency content below and above the specified low and high frequency is set to zero. The result is then converted back into the time domain by the inverse Fourier transform.

4.3.4 Play signal on DSTF

This function is used to play a given signal, and returns the recorded acceleration. Prior to the signal being played it undergoes signal conditioning. The conditioning is necessary to reduce the transient effects (undesired acceleration levels at the start and end of the signal, see Figure 4.5) caused due to the boundary conditions.

To mitigate this issue a windowing function was used, see Figure 4.4, with a ramp up/down time of 0.25 second. This function is applied by multiplying the input signal by the window, thus ensuring that the value and derivative of the signal starts and ends with zero. The selected window profile was a half Hanning window, as it ramps from zero to one (for the first half of the window, vise versa for the second half) and the derivative of the beginning and end of the ramp is zero.

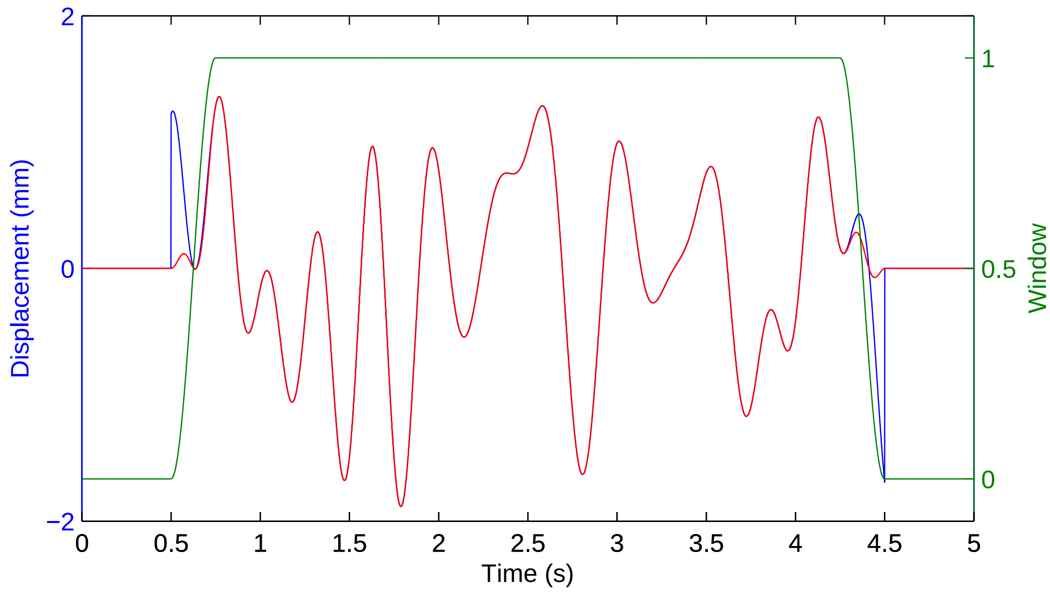


Figure 4.4: Example of windowing function: —: Signal; —: Windowed signal; — : Windowing function

With a stimuli length of four seconds (Section 4.4 provides motivation for the stimuli duration), it is important to minimise the ramp duration, so that the majority of the signal is preserved. The ramp duration was modified to minimise the ramp time while still significantly reducing the transient accelerations. With a ramp length of 0.25 seconds, the transient accelerations appears to be minimal, as shown in Figure 4.5.

4.3.5 PSD estimate

The frequency content of the signals was quantified by using PSD functions. The PSD functions of both the W_k weighted displacement profile and W_k

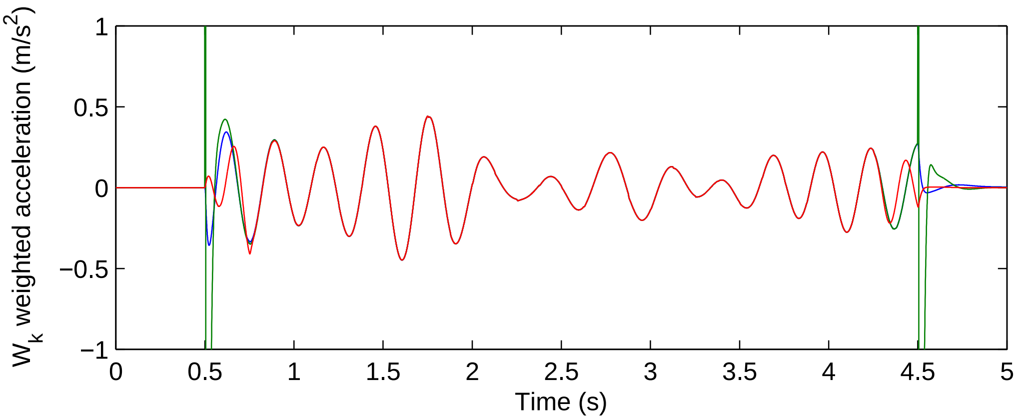


Figure 4.5: Windowing function: —: Desired acceleration profile; — : Signal acceleration profile; —: Windowed signal acceleration profile

weighted acceleration where calculated using the `pwelch.m` function in MATLAB with a Hanning window of one second length, an overlap of 50% and a block length (NFFT) of 8192.

4.3.6 Calculate error

Since the square root of the area under a PSD is the r.m.s. value of the signal (Griffin, 1996), the error was calculated as the square root of the integral of the absolute difference between the PSD of the desired acceleration and the PSD of the measured acceleration, as shown by:

$$error = \sqrt{\sum_{f=2}^{25} |PSD_{Measured}(f) - PSD_{Desired}(f) \cdot (2\pi f)^{-2}|} \tag{4.3.3}$$

Where $error$ is the magnitude a human weighted r.m.s. acceleration.

If the error is less than 15% of the desired acceleration then the iteration process of the algorithm is interrupted and the filtered time signal is returned. If not the loop is continued. The algorithm will be interrupted if the loop counter is greater than than 10, and an error will be displayed.

4.3.7 Calculate new transmissibility estimate

If the error is greater than 15% a new transmissibility estimate will be calculated. Equation 4.3.4 shows how the new estimate is calculated.

$$H_{est(n+1)} = H_{est(n)} \cdot \frac{PSD_{Measured}}{PSD_{Desired}} \tag{4.3.4}$$

Where $H_{est(n)}$ is the transmissibility estimate in-putted into the filter to generate the signal and n is the iteration number.

4.3.8 Create signal for JND

For the JND threshold testing procedure a reference stimulus and a set of alternative stimuli signals are required. The alternative stimuli signals where created by multiplying the reference stimuli signal by 0,125 dB (i.e. 1,4%) increments up to 3 dB (i.e. 41,3%). As a final check, the set of alternative stimuli are played to the subject and the measured acceleration profiles verified to ensure that the weighted r.m.s acceleration levels are appropriate.

4.4 JND threshold testing

The Up-Down-Transformed-Response (UDTR) testing procedure was used with a three down, one up rule (The level of the alternative stimuli is decreased after three positive responses and increased after one negative response). This approach was chosen as it provides the threshold at a 80% correct response. This is more than half way between a 'chance' (50%) response and a certain (100%) response Morioka and Griffin (2000).

The stimuli were presented via the gated pedestal method. The stimuli were presented in pairs and included a 4 second stimulus, a 1 second pause and a second 4 second stimulus. (Chosen as Morioka and Griffin (2000) presented a similar study on seated whole-body vibration, with this presentation method and these durations, allowing for the results of this study to be compared to literature). The order in which the reference and alternative stimuli were presented was randomised. The subjects were required to wear a headset playing white noise at a level of 75 dBA during the JND threshold tests to eliminate the noise from the hydraulic power packs and actuator.

The following question was asked to the subject after being exposed to the pair of stimuli: "*Did you feel the first or the second stimulus to be the greater?*" If the subject identified the greater vibration correctly the response was deemed to be positive otherwise it was deemed negative.

A MATLAB code, `getJND.m` (Appendix B.5), was implemented to automate the UDTR testing procedure, ensuring that the correct alternative levels are presented and that the order of the stimuli are randomised. An operator was present during the tests to ensure that the test is conducted safely and to enter the subject responses.

Figure 4.6 provides the example of a typical JND threshold test using the UDTR procedure (three-down and one-up rule). The test initiates by playing alternative stimulus with the same magnitude as the reference stimulus. In this example a positive response was received after trial number 1, so the alternative stimulus level remained unchanged for trial number 2. After trial number 2, a negative response was received, so the alternative stimulus level in the following trial was increased by one step (i.e. 1.4%). Subsequently, after trial number 10, three positive responses in a row where recoded (see P_1),

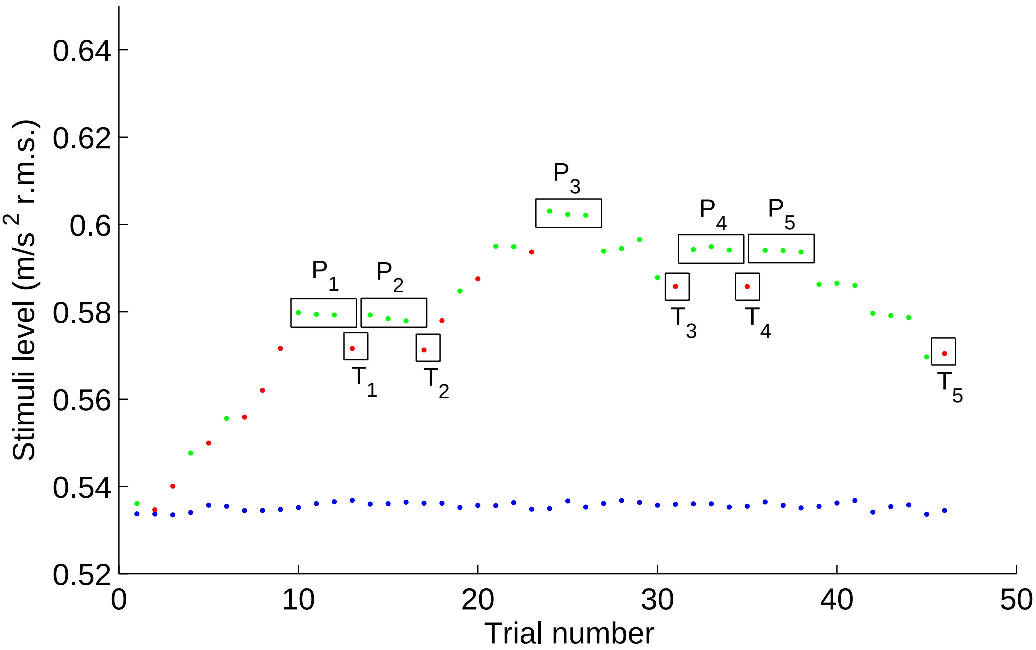


Figure 4.6: A typical JND threshold test procedure using `getJND.m`. ●: Reference stimulus; ●: Alternative stimulus with positive response; ●: Alternative stimulus with negative response.

thus the alternative stimulus level for trial number 13 was decreased by one step. After trial number 13, a negative response was recorded (see T_1) so the alternative stimulus magnitude was increased by one step. The combination of a peak and a trough is called a reversal.

The algorithm will continues until five reversals are complete, or if the desired alternative stimuli is greater than 3 dB (which did not occur during any of the tests). The data is then post-processed to calculate the relevant difference thresholds as shown in Equation 4.4.1.

$$\triangle I = \frac{\sum_{i=2}^{5} P_{(i)} - P_{ref(i)} + \sum_{i=2}^{5} T_{(i)} - T_{ref(i)}}{8} \tag{4.4.1}$$

Where $\triangle I$ is the difference threshold in m·s^{-2} r.m.s.; P_i and $P_{ref(i)}$ are the average r.m.s. alternative stimulus level and reference stimulus level respectively of the three peak values for reversal i; T_i and $T_{ref(i)}$ are the values of the alternative and reference stimuli for the trough of reversal i. Data from the first reversal was discarded in order to reduce the effect of starting errors on the JND threshold estimate.

The relative difference threshold, C, can be calculated as shown in Equation 2.5.1 using the difference threshold, $\triangle I$, as calculated in Equation 4.4.1 and I being the average magnitude of the reference stimuli for the reversals.

Chapter 5

Results

The comfort onboard the S.A. Agulhas II for the duration of the 2013-2014 Antarctic relief voyage was assessed in accordance with ISO 2631-1 for locations in the Bridge and Operations Room. The measured acceleration data was divided into 256 second intervals and quantified r.m.s. and VDV metrics were calculated. The results from this analysis are presented in Section 5.1. Case studies, the selection of which were based on the above mentioned analysis, were then preformed to analyse the comfort in specific conditions. These conditions included sailing in calm seas, rough seas, thin ice, thick ice and Dynamic Positioning (DP) on station.

A "real world" vibration stimulus was subsequently selected from these conditions. Just-noticeable-difference (JND) tests were conducted in a laboratory environment to determine the smallest change in vibration level that is perceptible to human subjects. These levels serve to inform studies on ship response feedback to human operators (Soal and Bekker, 2013), or to afford designers and shipbuilders information on the smallest comfort improvement that is perceptible.

5.1 Comfort during the voyage

Figure 5.1 presents the weighted r.m.s. acceleration values for the tri-axial measurements in the Bridge and Operations Room. Great variations in vibration magnitude can be seen between the two locations as well as during the different phases of the voyage. Low levels of vibration are reported during periods when the ship is pushed up against ice, while higher levels where recorded while sailing on open waters and when stuck in ice.

The statistical distribution of all the weighted r.m.s. acceleration levels are represented by a box-and-whisker diagram as shown in Figure 5.2. The the mean values weighted r.m.s. values are provided in Table 5.1.

Weighted acceleration levels in the Bridge were found to be significantly greater than those in the Operations Room. Weighted acceleration levels in the

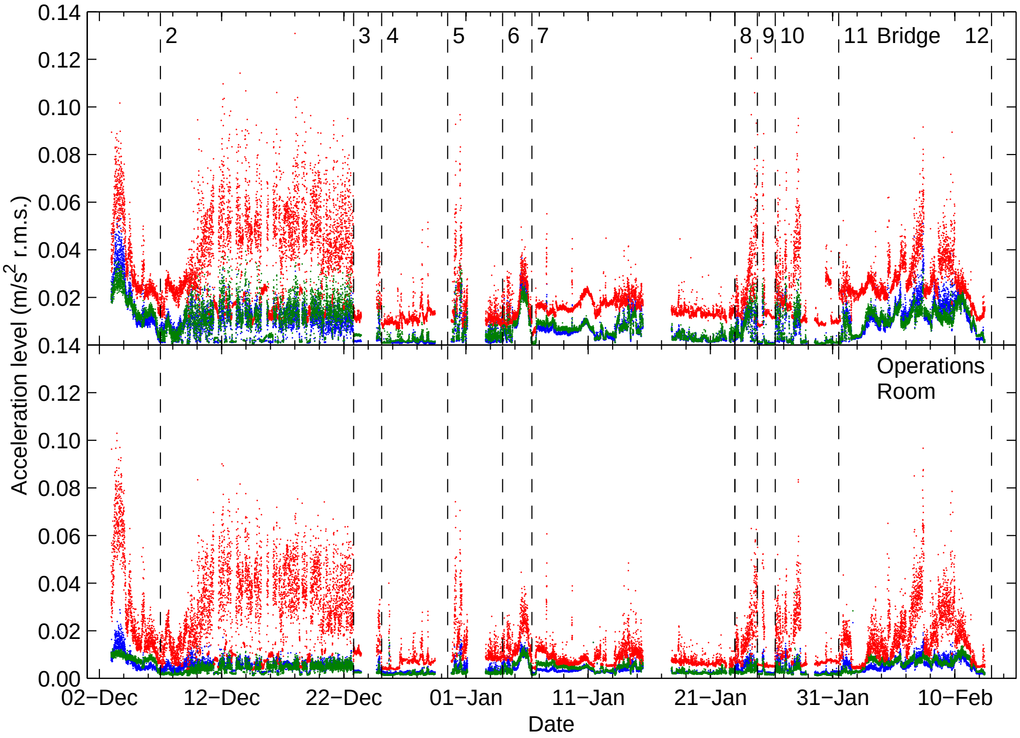


Figure 5.1: Comparison of the weighted r.m.s. acceleration levels for both the Bridge and the Operations Room: ●: x; ●: y; ●: z.

Table 5.1: Mean values of the weighted r.m.s. acceleration levels for the duration of the measurement

Mean (mm·s^{-2} r.m.s.)		
Direction	Bridge	Operations Room
x	8,1	4,6
y	8,7	4,4
z	25,3	17,3

vertical (z) direction dominated those in the horizontal (x and y) directions for both the Bridge and Operations Room. Only slight variation exists between the vibration magnitudes of the horizontal (x and y) directions.

The crest factor reflects the impulsiveness of the vibration. ISO 2631-1 suggests that for vibrations with crest factors above 9 the r.m.s. evaluation method is not sufficient as the signal is not considered to be stationary random. This implies that the r.m.s. magnitude will be sensitive to the duration of the analysis. Therefore the r.m.s. metric is not a robust metric for the representation of the signal magnitude in these cases.

This threshold along with the crest factors for all the accelerations are shown in Figure 5.3. The crest factors in the Bridge are above 9 for 13%, 21%

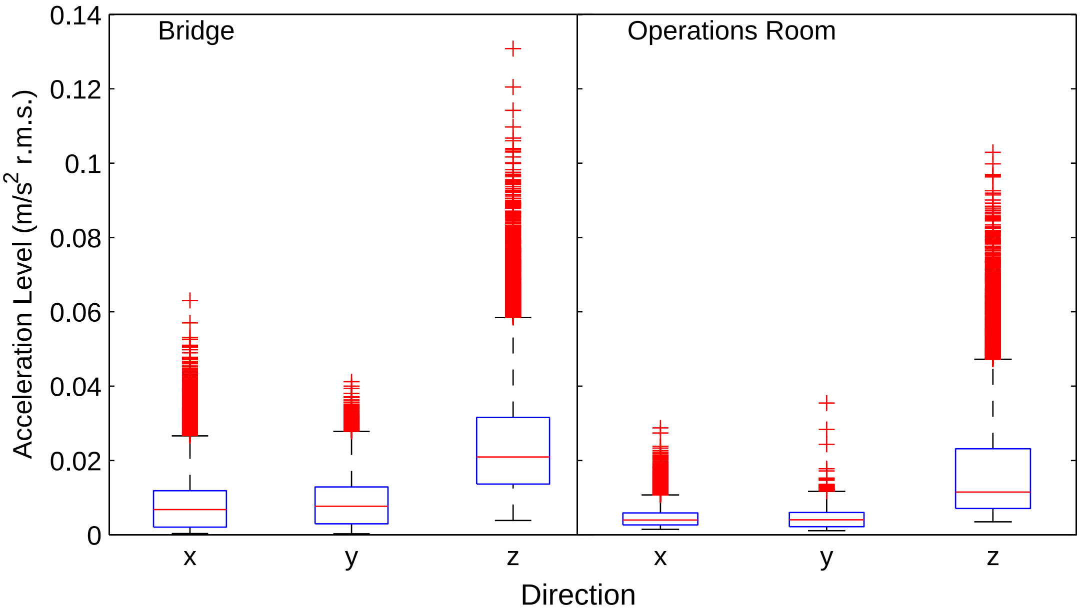


Figure 5.2: Box-and-whisker diagram showing the distribution of accelerations levels during the voyage of the Bridge and Operations Room in the x (fore-aft), y (lateral) and z (vertical) directions.

and 21% of the measurement duration in the x,y and z directions respectively. In the Operations Room they are above the threshold for 9%, 10% and 33% of the measurement duration. Crest factors in the z-direction of the Bridge are significantly greater in that than in the Operations Room. This shows that the vibration has an impulsive component, with the z direction in the operations Room being the most impulsive, and that the r.m.s evaluation is not sufficient to evaluate the vibration, thus additional metrics, such as VDV, should also be considered.

In addition to the r.m.s. metric, the VDV is reported (Figure 5.4) as it is a more suitable metric for the evaluation of impulsive (high crest factor) vibration than the r.m.s. metric. Figure 5.4 shows VDV's for 256 second time periods. The same trends as seen in the r.m.s. evaluation are also present in the VDV. Vibration in the vertical (z) direction is dominant in both the Bridge and Operations Room. Vibration in the Bridge is greater in the Bridge than in the Operations Room. The total VDV's for the measurement duration are provided in Table 5.2.

It is useful to report the point vibration total value which incorporates all three directions since the combined vibration discomfort is influenced by vibrations in the horizontal and vertical directions Griffin (1996). As the body is only in contact with one vibrating surface, the Point Vibration Total Value (PVTV) is equal to the Overall Vibration Total Value (OVTV). Figure 5.5 shows the overall vibration total values calculated for the duration of the voy-

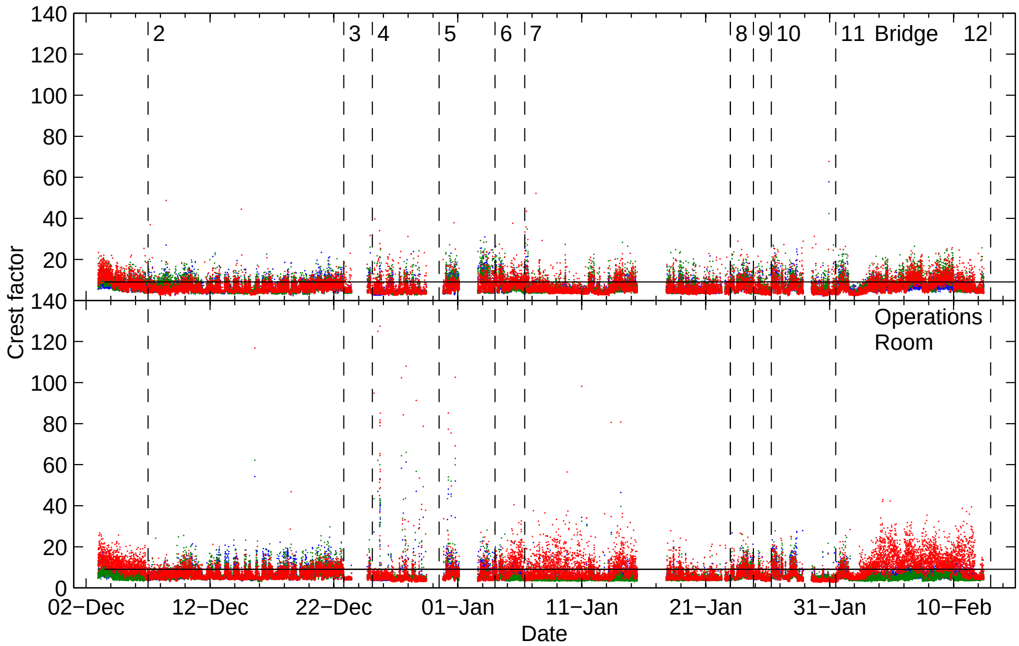


Figure 5.3: Comparison of crest factors for both the Bridge and the Operations Room: •: x; •: y; •: z; −: Crest factor = 9

Table 5.2: Total VDV's for the measurement duration

	Total VDV ($m{\cdot}s^{-1.75}$)	
Direction	Bridge	Operations Room
x	1,36	0,64
y	1,22	0,63
z	3,19	2,91

age. The maximum point vibration total values of the Bridge and Operations Room where 136 and 105 $mm{\cdot}s^{-2}$ r.m.s. respectively. ISO 2631 does not define a limit for vibration magnitude however it does provide likely reactions to various vibration levels in public transport in which vibration magnitudes less than 315 $mm{\cdot}s^{-2}$ r.m.s. where classified as "not uncomfortable". The maximum recorded overall vibration total values in the Bridge and Operations Room are less than half of the "not uncomfortable" reaction, thus could be considered as such. The worst case OVTVs in ice where of a similar magnitude to that while in rough seas.

The VDV values of the x, y and z directions can be combined, as shown in Equation 2.2.1, resulting in the overall VDV, see Figure 5.6. The maximum overall vibration dose value for the Bridge and the Operations Room where 1,07 and 0,985 $m{\cdot}s^{-1.75}$, while the minimum overall VDVs where 0,0198 and 0,0187 $m{\cdot}s^{-1.75}$ respectively. The overall total VDV's for the duration of the

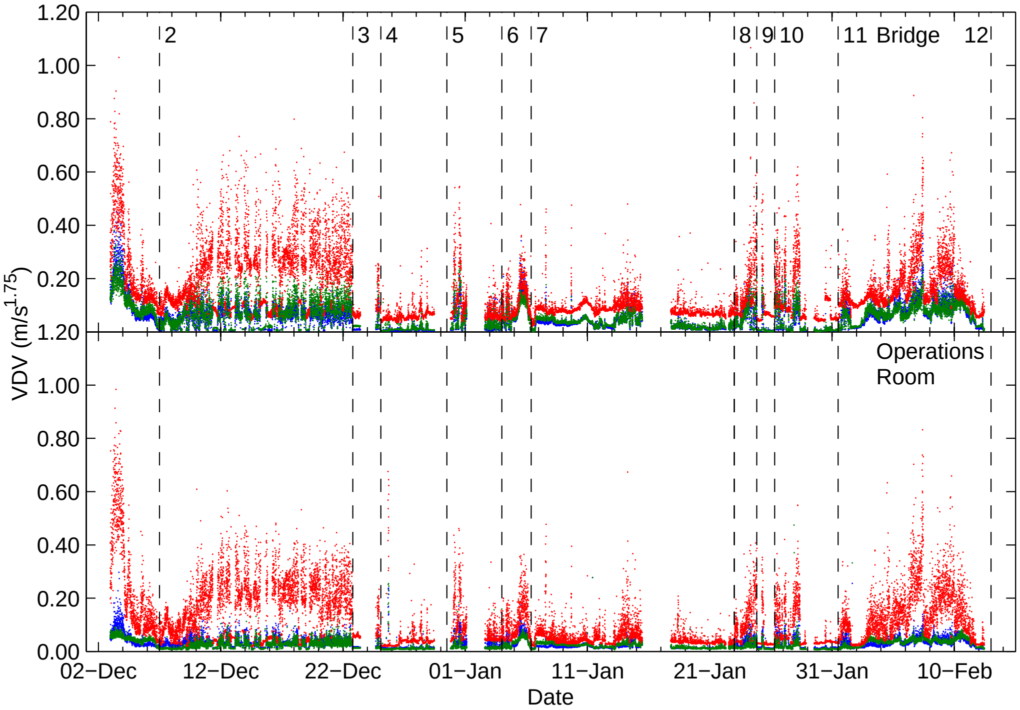


Figure 5.4: Comparison of VDV's for both the Bridge and the Operations Room: •: x; •: y; •: z.

measurement is 3,24 and 2,91 m·s$^{-1.75}$ in the Bridge and Operations Room respectively. The OVDVs in rough seas are significantly larger than those in ice, even though it was found that the OVTVs while in ice are similar in magnitude to those in rough seas. This is due to the impulsive vibration (high crest factors) while in rough seas (due to slamming). The VDV metric is more sensitive to peaks than the r.m.s. evaluation method due to the fourth power averaging, thus the larger the crest factor, the larger the VDV and OVDV.

ISO 2631-1 stipulates that the perceptibility of vibration is associated with the greatest peak acceleration measured at that position. Therefore the value of importance with respect to perceptibility in this study is the maximum peak acceleration value of the x, y and z directions for each time interval. The ISO 2631-1 stipulates that the median perception threshold is approximately 0,015 m·s^{-2}, the interquartile range of responses may extend from about 0,1 m·s^{-2} to 0,2 m·s^{-2} peak. As such, 75%, 50% and 25% of people will be able to feel a vibration with a peak weighted acceleration of 0,02 m·s^{-2}, 0,015 m·s^{-2} and 0,01 m·s^{-2} respectively. Figure 5.7 shows the distribution of peak acceleration values calculated for the assessment of perceptibility. If the median threshold is applied, 50% of alert fit persons would have been able to perceive vibration for 99,1% and 96,8% of the measurement duration in the Bridge and Operations Room respectively. It must be noted that since the assessment for vibration is based on the peak amplitude, if the calculated perceptibility value is above

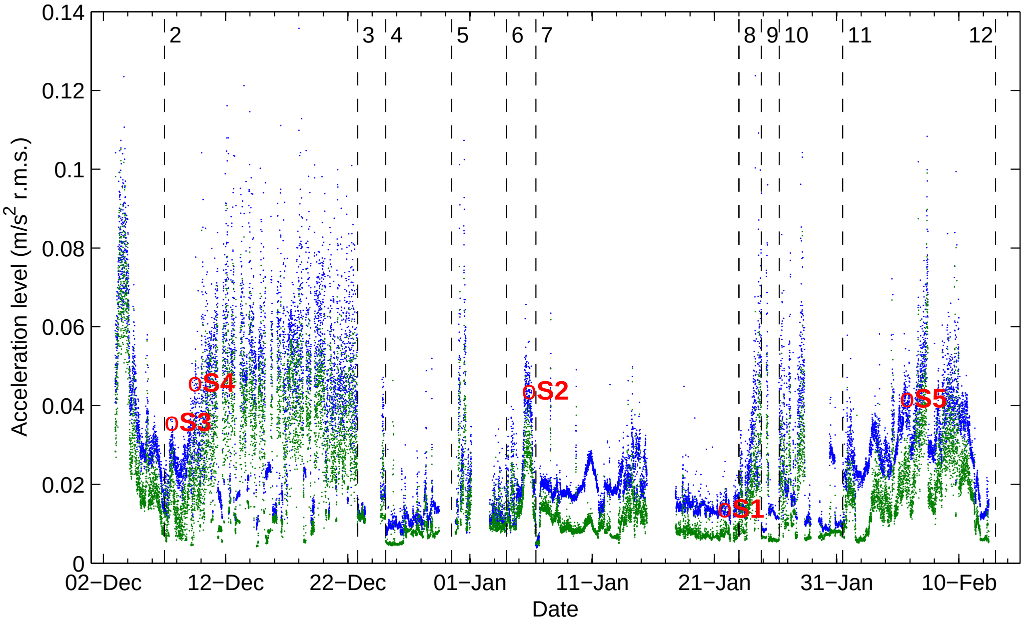


Figure 5.5: Comparison of Overall Vibration Total Value for both the Bridge and the Operations Room: •: Bridge; •: Operations Room; o **S1**: Slight seas; o **S2**: Rough seas; o **S3**: Thin ice; o **S4**: Thick ice; o **S5**: DP moderate seas;

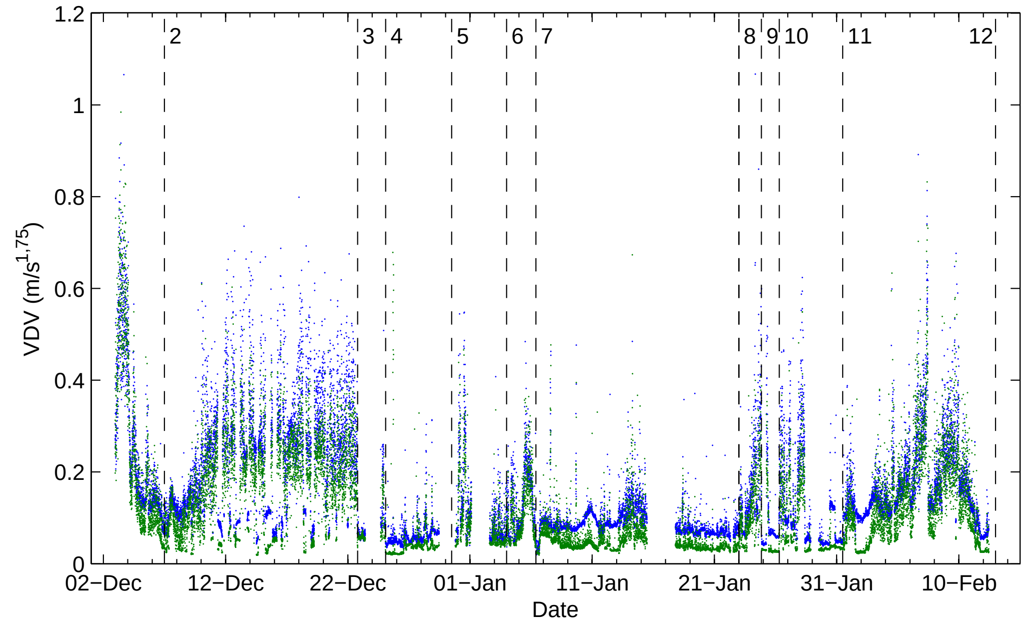


Figure 5.6: Comparison of Overall Vibration Dose Values for both the Bridge and the Operations Room: •: Bridge; •: Operations Room.

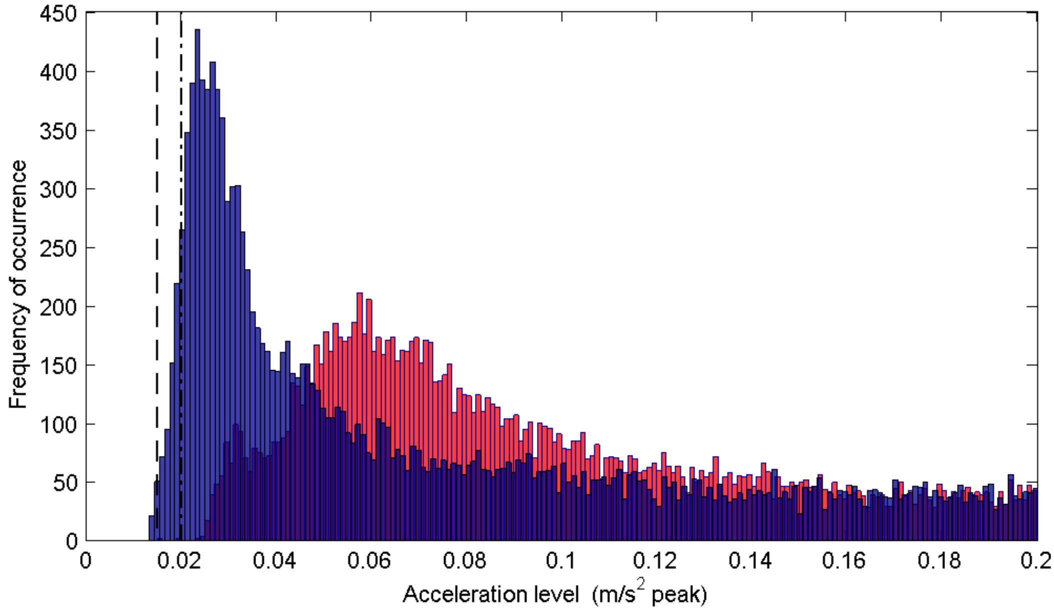


Figure 5.7: Histogram of peak acceleration levels for both the Bridge and the Operations Room, used for the assessment of perceptibility: number of bins = 2000; ■: Bridge; ■: Operations Room.; −−: Median perception threshold of 0,015 m·s^{-2}; − · −: Upper quartile perception threshold of 0,02 m·s^{-2}

the threshold for perception, it implies that vibration could be felt for some portion of the 256 second duration and not necessarily that entire duration.

The filters used to obtain the weighted acceleration levels are specified in ISO 2631-1. Although the standard specifies the same filters for both seated and standing comfort evaluations, the design of these filters has been heavily influenced from research on seated subjects (Taylor *et al.*, 2013). In a recent study Thuong and Griffin (2011) have shown that, unlike the vertical weighting filter, the horizontal weighting filter is not consistent with their experimental results for horizontal accelerations of standing persons, for the frequency range from 0.5 to 16 Hz. The filter proposed by Thuong and Griffin (2011) and those proposed in ISO 2631-1 are compared in Figure 2.2. Although there are clear differenced between the horizontal filter proposed by Thuong and Griffin (2011) and W_d proposed in ISO 2631, the use of the standard weighting filter is deemed appropriate as it will provide conservative exposure levels.

5.2 Case studies

In order to make a more informed decision as to which stimuli to choose for the JND testing, specific scenario's where selected and further investigated. Five different operating conditions where identified, and a 256 second interval was selected for each operating condition based on the median of the overall vibration total value (Figure 5.5). The operating conditions for each of the five scenarios are provided in Table 5.3. The Swell heights were obtained from the ship's log book, ice properties were obtained via continuous visual observations. The ship speed and propeller rotational speed were obtained from the ships Central Measurement Unit. Details of the unweighted frequency content are presented in Figure 5.8 and comfort assessment in Table 5.4.

Table 5.3: Meta-data for case studies

	Slight seas	Rough seas	Thin ice	Thick ice	DP moderate seas
Swell height (m)	1	7	-	-	4
Ice concentration (%)	-	-	70 to 90	80 to 100	-
Ice thickness (m)	-	-	0,6 to 0,8	1 to 1,8	-
Floe diameter (m)	-	-	20	$>$ 2000	-
Speed (km/h)	21,9	21,5	20,7	12,2	0
Propeller speed (rpm)	132	128	99	140	130

Slight seas resulted in the lowest weighted vibration levels while DP in moderate seas resulted in the highest weighted vibration levels. For all the cases, the weighted vibration levels in the Bridge were greater than the Operations Room. Weighted vibration levels in the vertical (z) direction are dominant for both the Bridge and Operations Room. The peak weighted vibration levels in all of the cases are above the upper limit of the interquartile range for perceptibility, as specified by ISO 2631-1, thus the vibration would be perceptible to those aboard the ship in all five cases.

The engine speed of the 4 Wartsila 6L32 engines is constant at 750 rpm, and is evident in the frequency content in the vertical (z) direction in each of the cases at 12,5 Hz, both in the Bridge and Operations Room. The firing order of the engines, which each have 6 cylinders, is constant at 37,5 Hz. This can be seen in the frequency content in the vertical (z) direction in all of the cases for both the Bridge and Operations Room.

The blade pass frequency of the four bladed propellers is evident in the lateral (y) direction of the unweighted frequency content of the thin ice (propeller speed of 99 rpm thus blade pass frequency of 6,6 Hz) and thick ice (propeller speed of 140 rpm thus blade pass frequency of 9,3 Hz) cases. This excitation is due to the propeller blades impacting the ice.

The results from a modal analysis conducted using a finite element model of the vessel indicate bending modes at 2,6 and 4,3 Hz and a transverse bending mode at 3,7 Hz (STX Europe, 2010). No significant peaks in the frequency content for any of the selected cases exist at these frequencies. The frequency content of all the selected cases show peaks in the vertical (z) and fore-aft

Table 5.4: Comfort evaluation for five 256 second scenarios

Conditions — Position	Axis	Weighted acceleration (mm·s^{-2} r.m.s)	Crest factor	VDV (m·s$^{-1,75}$)	Overall ride value (mm·s^{-2} r.m.s)	Overall VDV (m·s$^{-1,75}$)	Perception (mm·s^{-2})
Slight seas							
— Bridge					14	0.070	139
	x	3	3.4	0.017			
	y	3	4.5	0.018			
	z	13	10.6	0.070			
— Operations Room					8	0.033	25
	x	3	3.8	0.015			
	y	3	4.1	0.014			
	z	7	3.7	0.033			
Rough seas							
— Bridge					44	0.205	286
	x	24	6.0	0.138			
	y	21	5.9	0.119			
	z	30	9.4	0.187			
— Operations Room					34	0.211	327
	x	10	5.2	0.060			
	y	12	4.3	0.062			
	z	31	10.6	0.210			
Thin ice							
— Bridge					36	0.165	150
	x	14	4.7	0.078			
	y	13	5.9	0.075			
	z	31	4.9	0.162			
— Operations Room					26	0.137	108
	x	8	6.0	0.043			
	y	3	5.7	0.014			
	z	25	4.7	0.137			
Thick ice							
— Bridge					46	0.198	146
	x	20	5.0	0.116			
	y	23	5.6	0.135			
	z	34	4.3	0.179			
— Operations Room					29	0.155	144
	x	11	5.1	0.064			
	y	04	4.7	0.019			
	z	26	5.5	0.154			
DP moderate seas							
— Bridge					42	0.203	233
	x	13	5.3	0.074			
	y	9	8.3	0.059			
	z	39	6.5	0.202			
— Operations Room					23	0.152	194
	x	6	5.7	0.031			
	y	5	6.6	0.028			
	z	22	8.8	0.151			

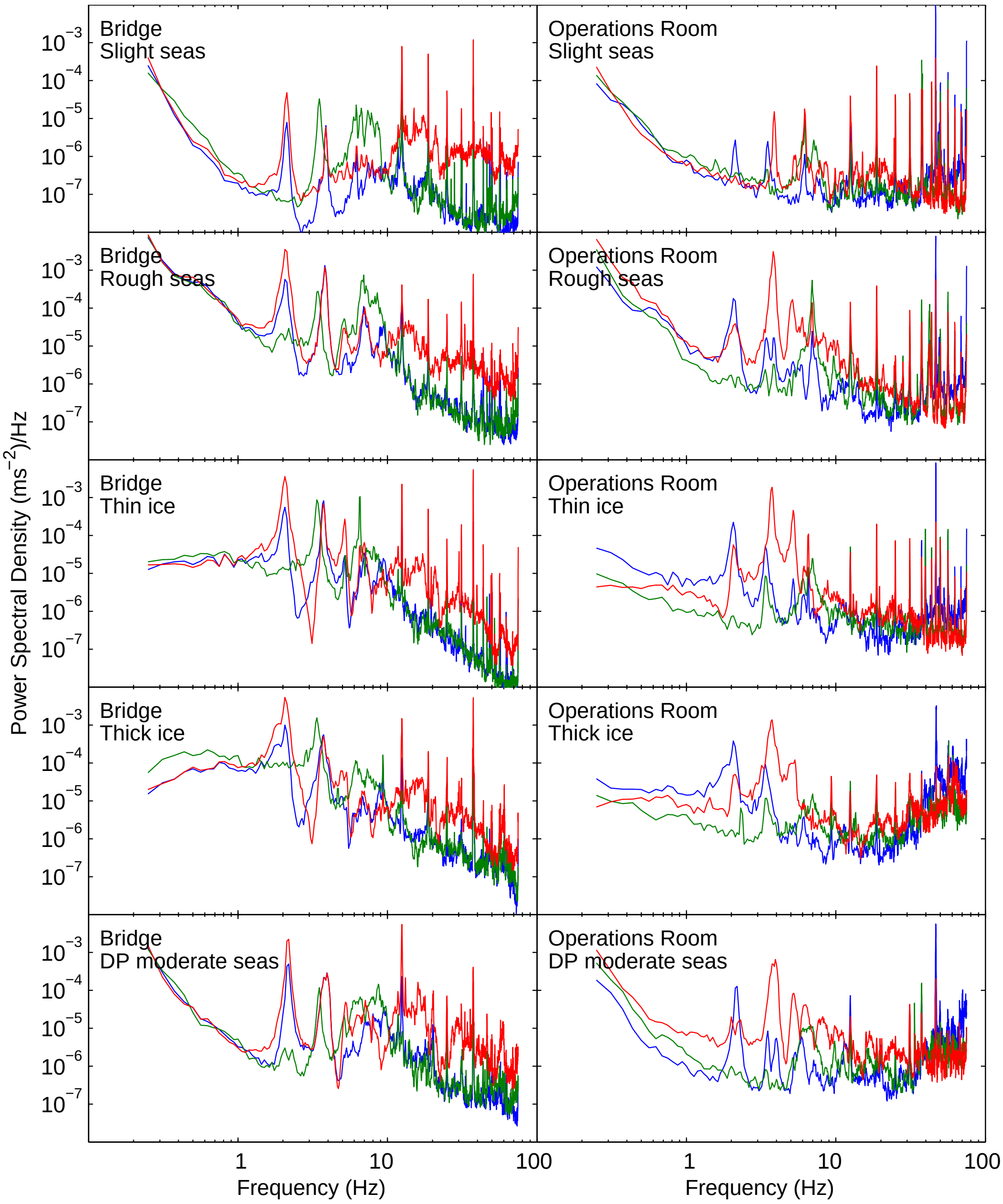


Figure 5.8: Comparison of unweighted PSD's for various sailing conditions in both the Bridge and the Operations Room: —: x; —: y; —: z.

(x) directions at 2,1 Hz and 3,8 Hz, while a peak in the lateral (y) direction exists at 3,4 Hz. These could be the modal frequencies, however an operational modal analysis would need to be conducted to confirm this observation.

A large amount of low frequency content is present in the selected cases that are in open water. A motion sickness assessment may be appropriate in such conditions, however this is beyond the scope of this project.

The frequency content of the lateral (y) direction from 1 to 4 Hz is distinctly greater when sailing in thick ice than in any other conditions. This may be due to the ice flows glancing off the bow of the ship, resulting in lateral (y) direction vibration.

5.3 Just noticeable difference threshold testing

Difference thresholds where determined during UDTR (3-up-1-down) procedures, preformed on six male and three female subjects, aged between 21 and 25 years. The stimuli used in the UDTR procedure were reconstructed using the algorithm described in Section 4.3.

The details of the recreated stimuli are subsequently presented. The results from the JND tests are then discussed in terms of the difference threshold and relative difference threshold. The results are finally compared to other JND investigations found in literature.

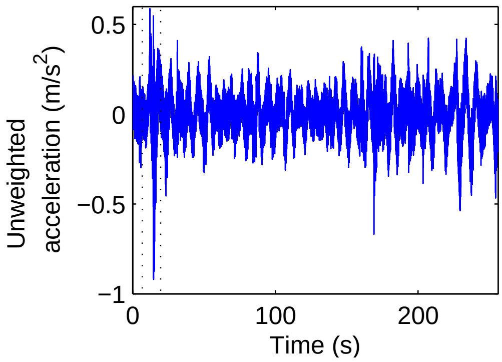
5.3.1 Vibration recreation

Two stimuli where used to investigate the JND threshold levels for whole-body vibration of standing persons. These vibration stimuli where recreated using the DSTF on nine subjects.

A 5 Hz sinusoidal stimuli with a magnitude of 500 mm·s^{-2} was selected as a stimulus. This provides a reference to existing studies, such as Morioka and Griffin (2000) that used a 5 Hz sinusoidal stimulus at a magnitude of 500 mm·s^{-2} and the same presentation type and exposure duration as this study.

The second vibration stimulus was selected from the case studies based on the following factors. Since the DSTF is only capable of recreating motion in the vertical (z) direction, the ship stimuli was chosen such that the majority of the vibration was in the vertical direction, thus eliminating the two ice conditions and the rough seas scenario. The slight sea scenario was not selected due to the low acceleration levels. The DP in moderate seas for the Bridge measurement position was selected to be the ship stimulus as it contains large vibration magnitudes, which were caused due to slamming. Future ship manufacturers may desire to improve the comfort in such conditions and thus knowledge of the JND threshold is useful information.

The 256 second acceleration time history of the DP in moderate seas condition for the Bridge measurement, shown in Figure 5.9a, was further investigated. A 4 second section was chosen, see Figure 5.9b, as it contained the slamming impulse that is associated with complaints from the captain and crew. This is a situation that ship designers and builders may desire to improve.



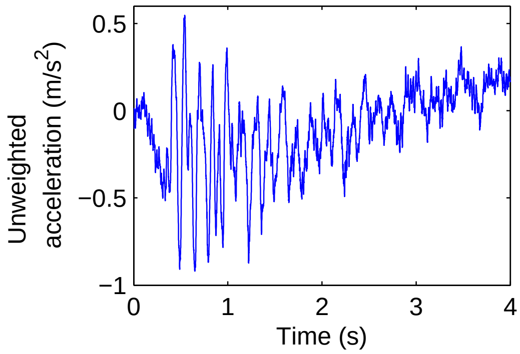


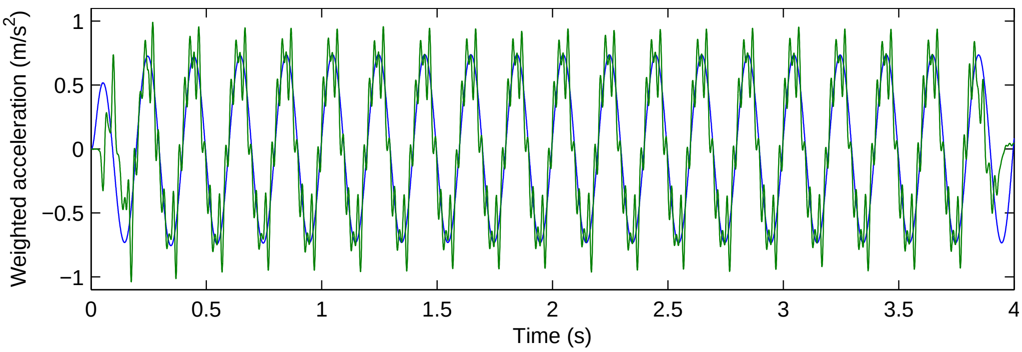
Figure 5.9: Selection of ship stimuli: (a) Time history of DP moderate seas condition; (b) Selected ship stimuli

The desired stimuli where recreated on the DSTF for each subject using the calibration procedure described in Section 4.3. Figures 5.10 and 5.11 present the W_k frequency weighted vibration of the desired and re-created stimuli, in both the time and frequency domain. The mean r.m.s. value of the recreated profiles were 524 mm·s^{-2} and 210 mm·s^{-2} for the sinusoidal and ship vibrations respectively, with a standard deviation across subjects of are 6,4 mm·s^{-2} and 8,9 mm·s^{-2}. The effect of the 'clicking' is evident for both the re-created sinusoidal and ship vibration. The frequency content of the sinusoidal stimulus shows harmonics of the 5 Hz fundamental frequency, occurring at 15, 25, 35, 45, ... Hz, which are created by the 'clicking' phenomenon. Likewise, the frequency content of the ship stimulus also shows high frequency content that was not desired, which was also introduced by 'clicking'.

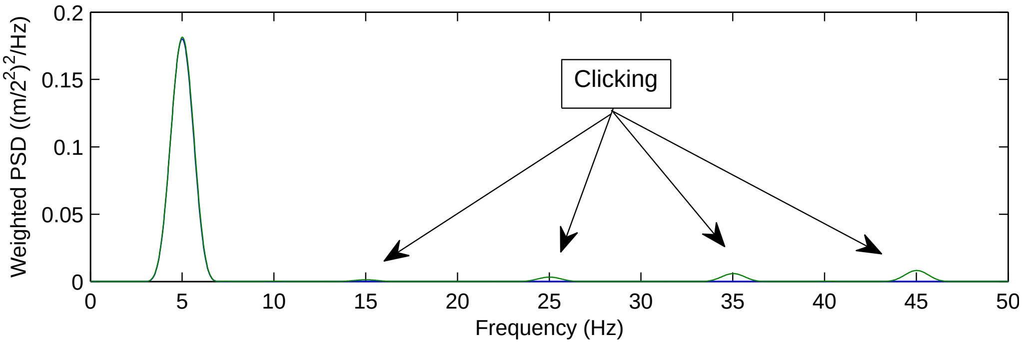
The algorithm used to calibrate the vibration stimuli (provided in Section 4.3) such that the DSTF recreated the desired vibration was deemed effective as the vibrations where calibrated to within 15% (definition of error shown in Equation 4.3.3) of the original stimuli for all the subjects.

5.3.2 Difference thresholds

Figure 5.12 shows the absolute difference thresholds of the nine subjects for both the sinusoidal and ship vibration, while Table 5.5 provides a statistical summary of the absolute difference threshold. It is clear that the difference thresholds were greater with the sinusoidal stimulus than the ship stimulus.



(a)



(b)

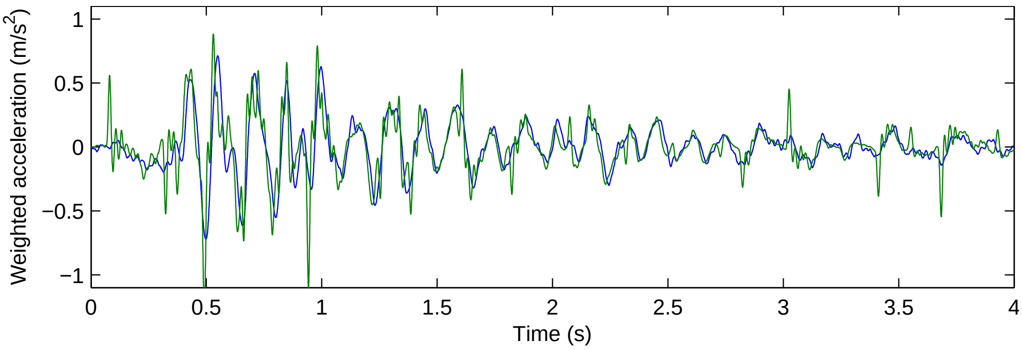
Figure 5.10: Comparison of desired and re-created sinusoidal vibration: —: Desired vibration; —: Re-created vibration: (a) Time domain; (b) Frequency domain (PSD properties: Fs: 2048; Window: Hanning; Window length: 1 second; Overlap: 50%; NFFT: 2048)

No significant correlation exists between subject age, weight or height and the absolute difference threshold for either of the stimuli (Spearman, $p > 0.05$).

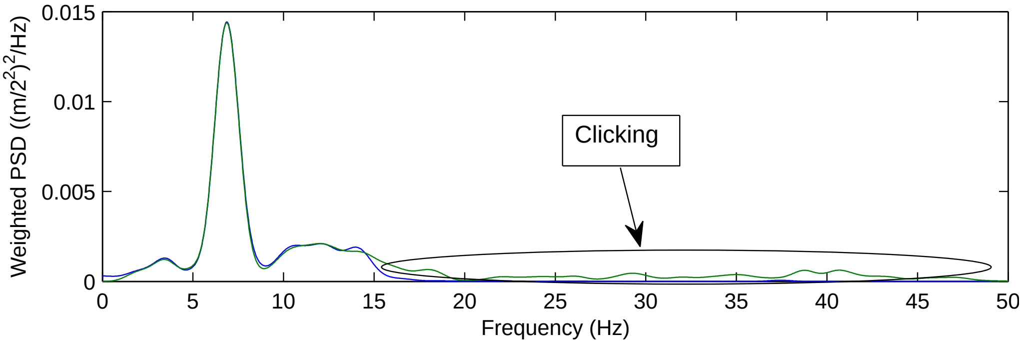
Table 5.5: Summary of difference threshold results (m·s^2)

Stimuli	Minimum	25th percentile	Median	75th percentile	Maximum
Sinusoidal	0.025	0.039	0.050	0.061	0.077
Ship	0.020	0.026	0.035	0.047	0.060

The JND test procedures of all nine subjects for both the sinusoidal and ship stimuli can be found in Tables A.2 and A.3 respectively. The longest UDTR (3-down-1-up) procedure for the sinusoidal and ship stimuli required 78 and 70 trials respectively while the mean procedure required 54 and 58 trials respectively. The average time taken to complete the entire testing procedure, including both stimuli calibration procedures, was 27 minutes wile the longest was 36 minutes and the shortest was 23 minutes.



(a)



(b)

Figure 5.11: Comparison of desired and re-created ship vibration: —: Desired vibration; —: Re-created vibration: (a) Time domain; (b) Frequency domain (PSD properties: Fs: 2048; Window: Hanning; Window length: 1 second; Overlap: 50%; NFFT: 2048)

5.3.3 Relative difference thresholds

It is important to note that the reference magnitudes of the two stimuli are different, with mean magnitude of the sinusoidal stimulus being 2,5 times greater than that of the ship stimuli. In addition to this the reference stimuli was not replicated exactly for each subject or even for each trial (Standard deviations for reference stimuli across subjects are 6,4 mm·s^{-2} r.m.s. and 8,9 mm·s^{-2} r.m.s. for sinusoidal and ship vibration respectively as a result of the experimental equipment). Therefore the relative difference threshold is important as it allows one JND threshold to be compared with another since it takes into account the reference stimulus level.

As such it is appropriate to investigate the percentage change in magnitude for which a subject could notice a difference in vibration magnitude. The percentages can be expressed as relative difference thresholds using the Weber fraction, $\triangle I/I$ (where $\triangle I$ is the absolute difference threshold and I is the reference magnitude). Figure 5.13 shows the relative difference thresholds for the sinusoidal and ship stimuli, expressed as a percentages, for the nine sub-

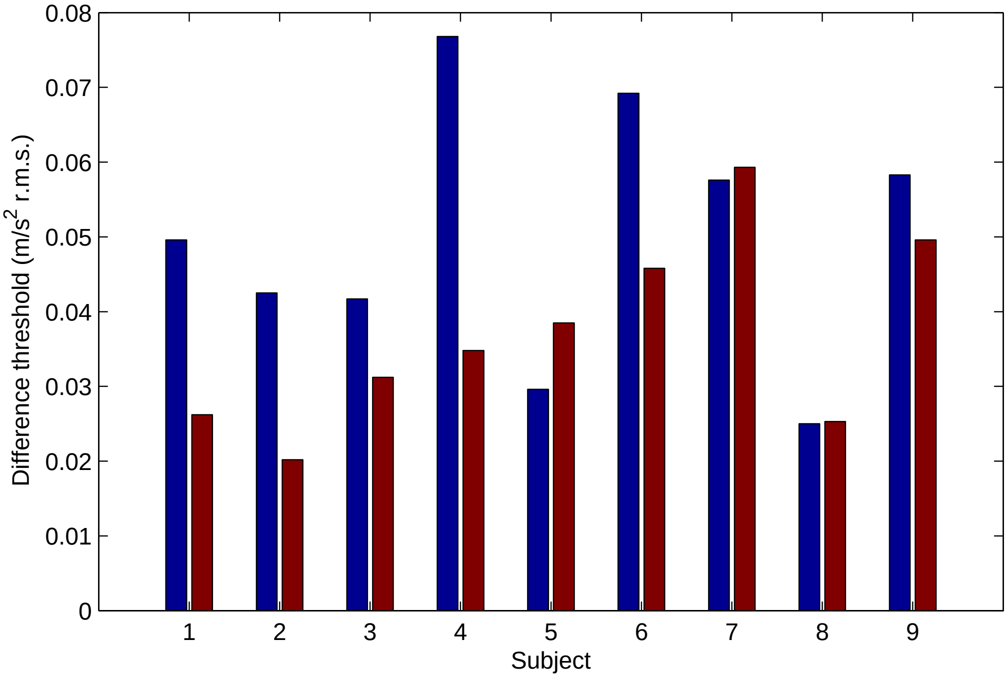


Figure 5.12: Difference thresholds for nine subjects measured for two stimuli: ■: Sinusoidal stimulus; ■: Ship stimulus.

jects, while Table 5.6 provides a statistical summary of the relative difference threshold.

Table 5.6: Summary of relative difference threshold ($\frac{\triangle I}{I} \cdot 100$) results (%)

Stimuli	Minimum	25th percentile	Median	75th percentile	Maximum
Sinusoidal	4,8	7,3	9,3	11,7	14,5
Ship	10,1	12,6	16,2	22,5	28,8

Relative difference thresholds ranged from 4,8% to 28,8% with mean values of 9,5% as opposed to 17,6% for the sinusoidal and ship stimuli respectively. Significant differences exist between the relative difference thresholds (Friedman, $p < 0.03$) of the sinusoidal and ship stimuli, with the ship stimuli having a larger relative difference threshold than the sinusoidal stimuli. This implies that either Webers law does not hold for difference thresholds of whole-body vibration in the standing position or that the frequency weighting W_k is not an appropriate weighting filter for evaluation of difference threshold for whole-body vibration of standing subjects.

No significant correlation exists between subject age, weight or hight and the relative difference threshold for either of the stimuli (Spearman, $p > 0.05$).

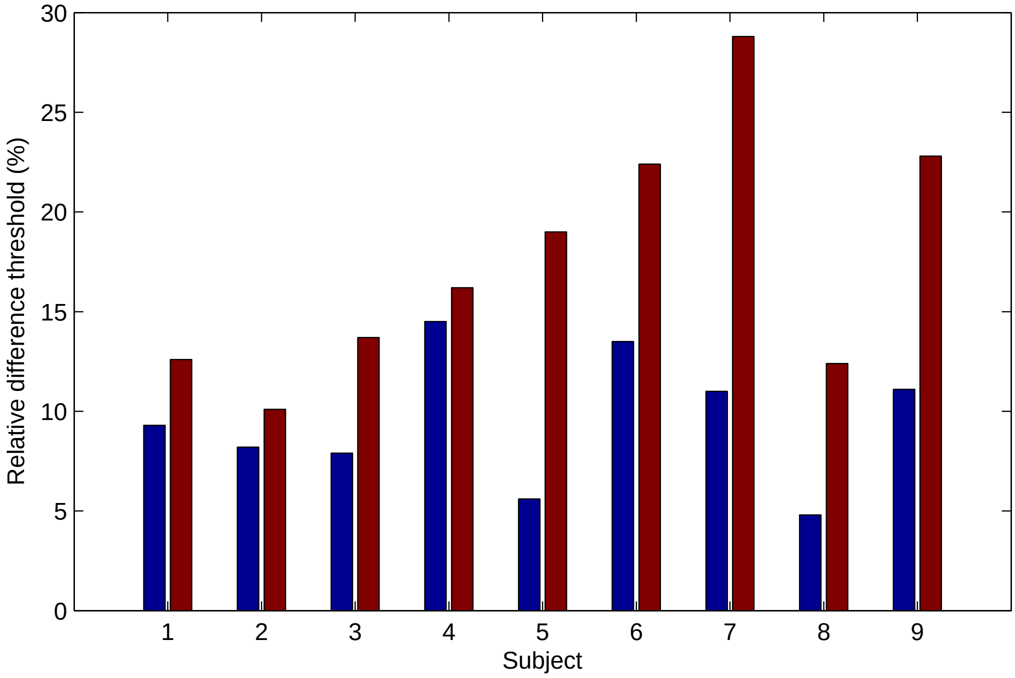


Figure 5.13: Relative difference thresholds ($\frac{\triangle I}{I} \cdot 100$) for nine subjects measured for two stimuli: ■: Sinusoidal stimulus; ■: Ship stimulus.

5.3.4 Comparison to previous JND studies

It has been assumed that the frequency weightings will convert the raw acceleration magnitudes into a metric of human comfort. As such, the authors of this study and those in literature first applied an appropriate frequency weighting to the time histories of the reference and alternative stimuli, then calculated the relative difference thresholds based on the weighted data.

It is expected that the relative difference threshold (where the magnitudes are human weighted) would be constant across the frequency range as the vibration magnitude should be normalized by the frequency weighting. Webers law suggests that the relative difference threshold is constant, irrespective of the reference amplitude.

The finding that the relative difference threshold is dependant on stimulus (level and/or frequency spectra) is inconsistent with some of those found in literature, such as Mansfield and Griffin (2000), Morioka and Griffin (2000) and Bellmann (2002) (frequency only), who show that no significant differences exist between relative difference thresholds for different magnitudes or frequency spectra. The results of Matsumoto *et al.* (2002), however, do indicate significant differences between relative different thresholds at different frequencies.

The relevant JND studies in literature for whole-body vibration are for seated subjects. However, it is expected that the results from this study should show some similarity to those found in literature since the accelerations used were human weighted with the W_k weighting filter, which has been deemed appropriate for the subjective evaluation of whole-body vibration for standing subjects (Thuong and Griffin, 2011).

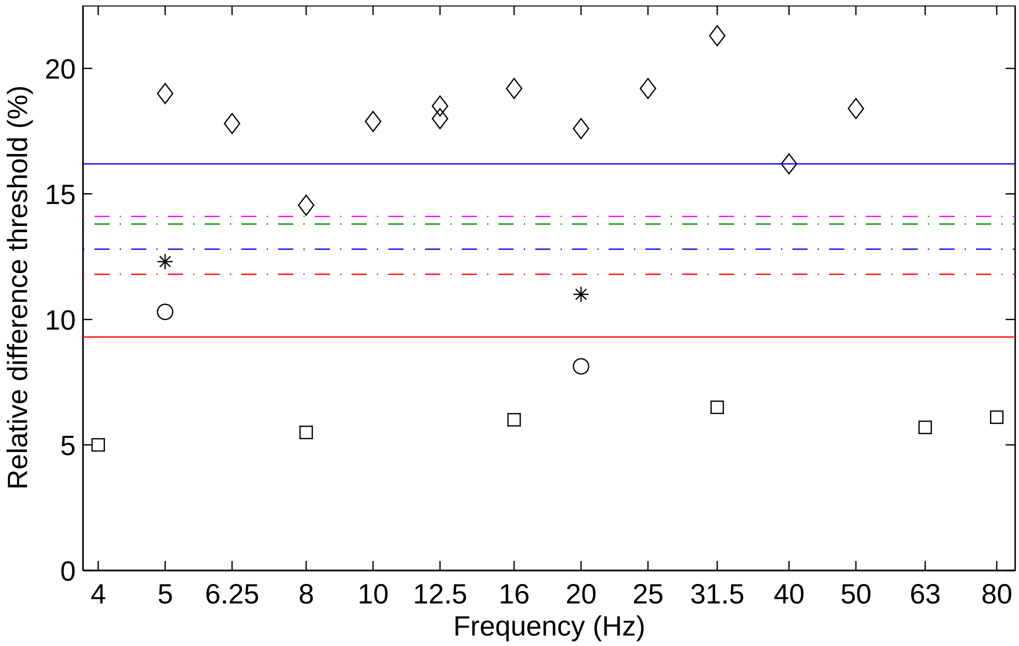
A comparison of the median relative difference thresholds determined by previous authors and in this experiment is provided in Figure 5.14. The sinusoidal stimulus (magnitude of 0,52 m·s^{-2} r.m.s of which more than 95 of the spectra at 5 Hz) shows a good correlation to the results obtained by Morioka and Griffin (2000) (Who preformed a similar test at the same magnitude and frequency, but on seated subjects), with a difference in relative difference threshold of only 1%. This could suggest that the W_k frequency weighting is appropriate for the assessment of whole-body vibration in the standing position (at a frequency of 5 Hz, with a level of 0,5 m·s^{-2} r.m.s.), however further testing is required to substantiate this finding.

5.3.5 Post testing subject assessment

Upon completion of the JND testing the subject were interviewed by the operator. The purpose of the interview was primarily to ensure that the testing did not cause any pain or other undesirable effects to the subject. None of the subjects reported any pain or health related effects. However, subjects did report that their feet got cold during the testing, due to them standing without wearing shoes on the cold aluminium platform.

The subjects where also questioned with respect to how they assessed the vibration. Most subjects could not identify the exact mechanism that they used to compare the paired stimuli. Subject 3 mentioned that he used his shoulders to compare the vibrations, while subjects 8 and 9 commented that they used the movement of their arms, hips and breasts to compare the vibrations.

Subject 8 also noted that the test felt awkward due to people being able to see the motion of her breasts. She recommended that female subjects should wear a sports bra to address this concern.



Legend

◇ : Bellmann (2002) (0,063 m·s^{-2} r.m.s.)

□ : Matsumoto *et al.* (2002) (0,7 m·s^{-2} r.m.s.)

○ : Morioka and Griffin (2000) (0,5 m·s^{-2} r.m.s.)

– · – : Mansfield and Griffin (2000) (Tarmac 0,2 m·s^{-2} r.m.s.)

– · – : Mansfield and Griffin (2000) (Tarmac 0,4 m·s^{-2} r.m.s.)

– · – : Mansfield and Griffin (2000) (Tarmac 0,8 m·s^{-2} r.m.s.)

– · – : Mansfield and Griffin (2000) (Pave 0,4 m·s^{-2} r.m.s.)

– : This experiment (Sinusoidal stimuli 0,52 m·s^{-2} r.m.s.)

– : This experiment (Ship stimuli 0,21 m·s^{-2} r.m.s.)

Figure 5.14: Comparison of whole-body vibration relative difference thresholds

Chapter 6

Conclusions and future work

The improvement of comfort aboard ships, especially ice breakers, is a relevant research topic as ship builders strive to increase the comfort of such vessels. The JND threshold is useful information to designers and shipbuilders as it provides information on the minimum comfort improvement that could be made such that those sailing on the ship would be able to notice an improvement.

In this project the vibration aboard the S.Agulhas II during the 78 day 2013-2014 relief voyage was measured in two locations, with a tri-axial accelerometer measurement both the Bridge and Operations Room. The 64 days worth of recorded data was evaluated according to ISO 2631-1 for a standing person, with a record length of 256 seconds per measurement.

Greater weighted r.m.s vibration levels where recorded in the Bridge than in the Operations Room for all three measurement directions, with vibration in the z direction being dominant in both the Bridge and Operations room.

The vibration was deemed to be perceptible for almost the entire duration of the voyage (more than 99% and 96% of the voyage in the Bridge and Operations Room respectively). It must be noted that due to the method of assessment for the perceptibility of vibration provided in ISO 2631-1, the vibration may not have been felt for that entire duration of each measurement, but it was perceptible for some portion of each of the 256 second measurements. Analysis with a shorter interval period may yield different results.

ISO 2631-1 is convenient as it provides a single measure (the overall vibration total value) for the evaluation of multi-axis vibration and a list of likely reactions with respect to vibration exposure. According to the list, **the vibration in both the Bridge and Operations Room are considered 'not uncomfortable' for the duration of the voyage**. Comfort complaints were however received from the captain and crew with respect to slamming.

The comfort should be further investigated on future voyages aboard the S.A.Agulhas II and other vessels. The investigations should include both vibration measurements and a record of subjective experiences of the crew and passengers during the voyage. Furthermore the investigation should be focused to yield improved assessment methods for long duration exposures aboard ships, possibly including the development of a list of likely reaction to various vibration levels found on ships, as this could assist with the future classification of comfort levels aboard such vessels.

The crest factor was above the ISO 2631-1 threshold of nine for a significant percentage of the voyage. This implies that the vibration is not stationary random, thus the r.m.s. metric is not a good representation of the signal. As such the VDV was also reported. The overall VDV was greater in the Bridge than in the Operations Room.

Based on the results of the comfort assessment, five individual case studies of specific conditions (including: slight seas, rough seas, thin ice, thick ice and DP moderate seas) where chosen to be further investigated. The time signals for these case studies where chosen by selecting a median overall vibration total value for each condition. The assessment of the case study included the ISO 2631-1 comfort assessment and a frequency content investigation.

Sailing in slight seas resulted in the lowest acceleration levels of all the case studies evaluated while thick ice resulted in the greatest. **When sailing in ice a high ratio of horizontal to vertical vibration exists**, possibly due to ice flows glancing off the bow of the ship. Slight and rough seas resulted in impulsive vibration (crest factor>9). Sailing in ice resulted in non impulsive (crest factor<6) vibration.

In open seas a large portion of the frequency content exists at frequencies below 1 Hz. **Therefore, a motion sickness assessment, based on the vibration data measured during this voyage and future voyages, should also be conducted.**

Two vibration stimuli were selected for which to determine the Just Noticeable Difference (JND) in vibration magnitude in the laboratory environment. One was a pure 5 Hz sinusoidal vibration with a W_k weighted magnitude of 0,5 m·s^{-2} r.m.s. This was chosen as the same experiment existed in literature for seated persons, thus allowing for the results of this project to be compared to those found in literature. The other stimuli was chosen to be a ship vibration stimuli as this would allow for the JND threshold of the ship for a specific condition to be investigated.

The specific ship stimuli was selected from the individual case studies. The DP moderate seas condition was chosen due to the high acceleration level of the vibration and the high ratio of vertical (z) to horizontal (x and y) vibration since the DSTF (used to recreate the vibration) is limited to motion in the vertical (z) direction. The 4 second stimulus to be used for the JND testing was selected from the 256 second DP moderate seas case study. It was selected as an interval in the signal which contained an instance of slamming on the ship hull.

A man-rated shaker platform, the Dynamic Seat Testing Facility (DSTF), was used to recreate the vibration stimuli in a controlled laboratory environment. An assessment of the DSTF was conducted that identified a problem which includes undesired high frequency vibration being super imposed on the desired stimulus as the direction of the actuator is reversed. Based on the investigations that where conducted, the problem is suspected to be due to wear and tear on the servo valve that controls the hydraulic actuator. Despite those limitations it was decided that the study could be continued provided that the output vibration of the DSTF was known. The PID control perimeters for the DSTF where selected by a trial and error method. It is recommended that prior to the use of the DSTF in future studies, the PID control parameters should be reselected with the aid of a standardised procedure.

The algorithm proposed in Section 4.3 was used to calibrate the desired stimulus such that they would be accurately recreated on the DSTF. The method was deemed effective as the stimuli where recreated to within 15%, despite the 'clicking' problem, for all of the subjects. **The mean r.m.s. acceleration of the sinusoidal and ship vibration, recreated on the DSTF for each subject, where 524 mm·s^{-2} and 210 mm·s^{-2} respectively**.

The UDTR (3-down-1-up) procedure was used for the JND threshold testing of the stimuli on six male and three female subjects. The average testing time per subject was 27 minutes with the longest test taking 36 minutes. The average number of trials to complete five reversals of the UDTR (3-down-1-up) procedure for the sinusoidal and ship stimuli were 54 and 58 trials respectively.

The JND threshold was determined in terms of a difference threshold and relative difference threshold. The median difference threshold for the sinusoidal and ship stimuli where evaluated as 50 mm·s^{-2} r.m.s. and 35 mm·s^{-2} r.m.s. respectively. No significant correlations exist between subject age, stature or weight and the difference threshold determined for either of the stimuli.

This study is the first that has been conducted to investigate the Just Noticeable Differecne (JND) in magnitude for standing subjects. No significant correlation exist between the relative difference thresholds of the sinusoidal and ship stimuli. This indicates that either Webers law (which states that the just noticeable difference of a stimulus is a constant proportion despite variation in intensity) **does not hold true for whole-body vibration of standing subjects or that the frequency weighting W_k is not a suitable frequency weighting for the assessment of comfort of standing whole-body vibration.**

No significant correlation exist between subject age, stature and weight and the relative difference thresholds. **The median relative difference threshold are 9,3% and 16,2% for the sinusoidal and ship vibration respectively**. As such, if a comfort improvement were to be desired aboard the S.A. Agulhas II during slamming, the improvement of the comfort would have to be greater than 16 % for the median person to be able to feel an improvement in comfort.

The results of the sinusoidal stimuli investigation correlated well with those found in literature, preformed on whole body vibration of seated subjects. As such it is thought that the vertical weighting filter

Wk is a suitable frequency weighting for the comfort evaluation of standing persons at 5 Hz.

Due to the clicking issue, the desired stimuli where not exactly recreated. Thus results from the JND tests should be interpreted with caution as they were based on stimuli which included clicking. It is recommended that the DSTF is repaired prior to further testing, such that the clicking issue is fixed. This would allow for more exact replication of stimuli.

Further testing is recommended on the two stimuli used in this project. It is proposed that tests at different magnitudes should be conducted to asses the applicability of Weber's law for the JND threshold of standing subjects. Other tests should also be conducted with stimuli at different frequencies, but at the same magnitude, to asses the validity of the vertical weighting filter W_k with respect to standing subjects.

JND threshold testing for the whole-body vibration of standing subjects should be conducted on more of the stimuli as found in literature for seated whole-body vibration. This would allow for further comparison of seated and standing vibration. The subjects for future JND studies should be carefully selected, to provide a sufficient sample size and range of demographics, including age, stature, weight, gender and race, such that they represent the general population.

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Appendices

Appendix A

Subject photographs & Levitt procedure trial histories

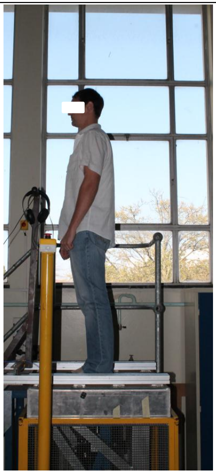
1	2	3
		
4	5	6
		
7	8	9
		

Table A.1: Picture of the subjects on the DSTF prior to testing.

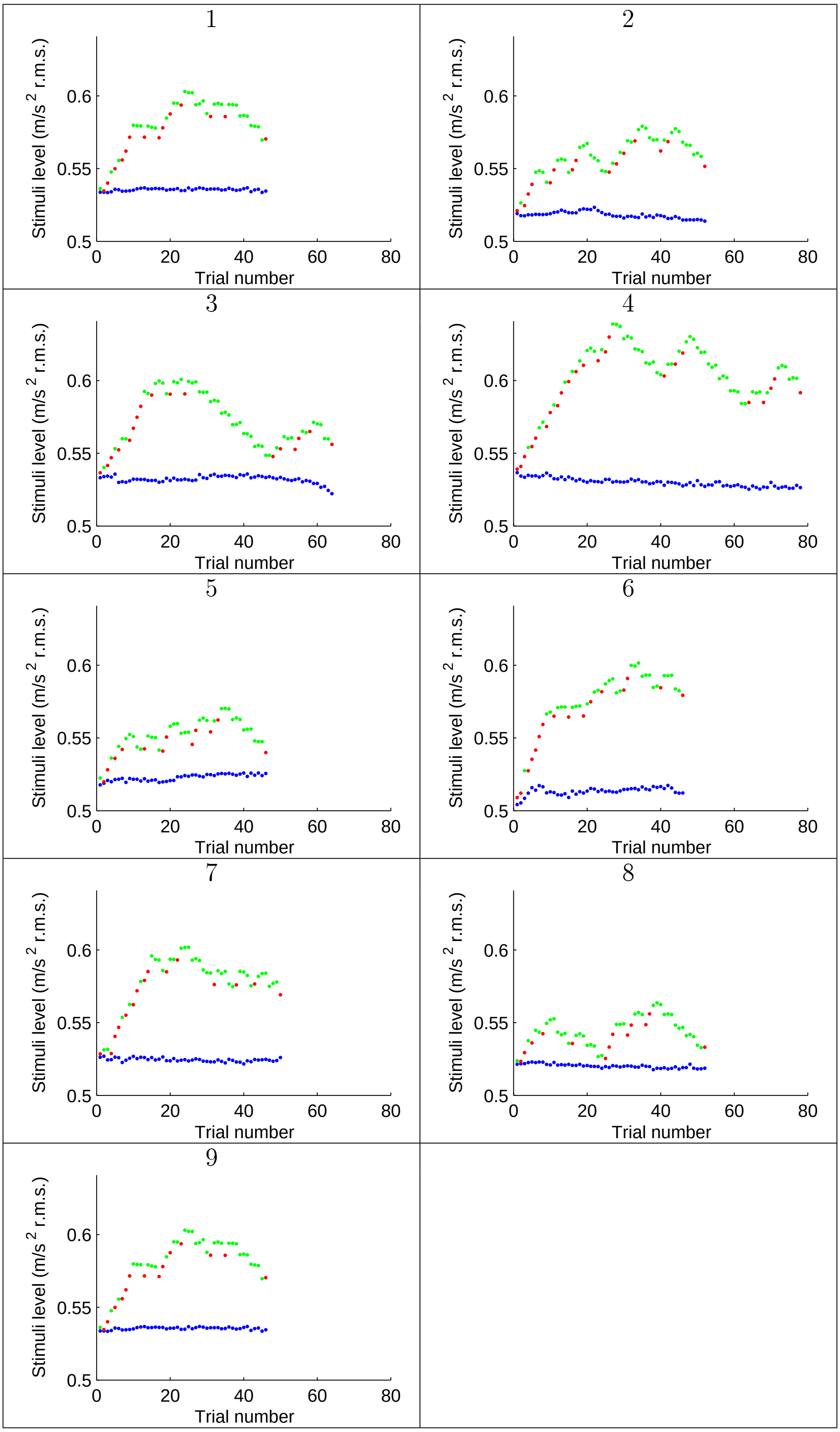


Table A.2: Levitt procedure trial history - **Sinusoidal stimulus** - Subjects 1 to 9

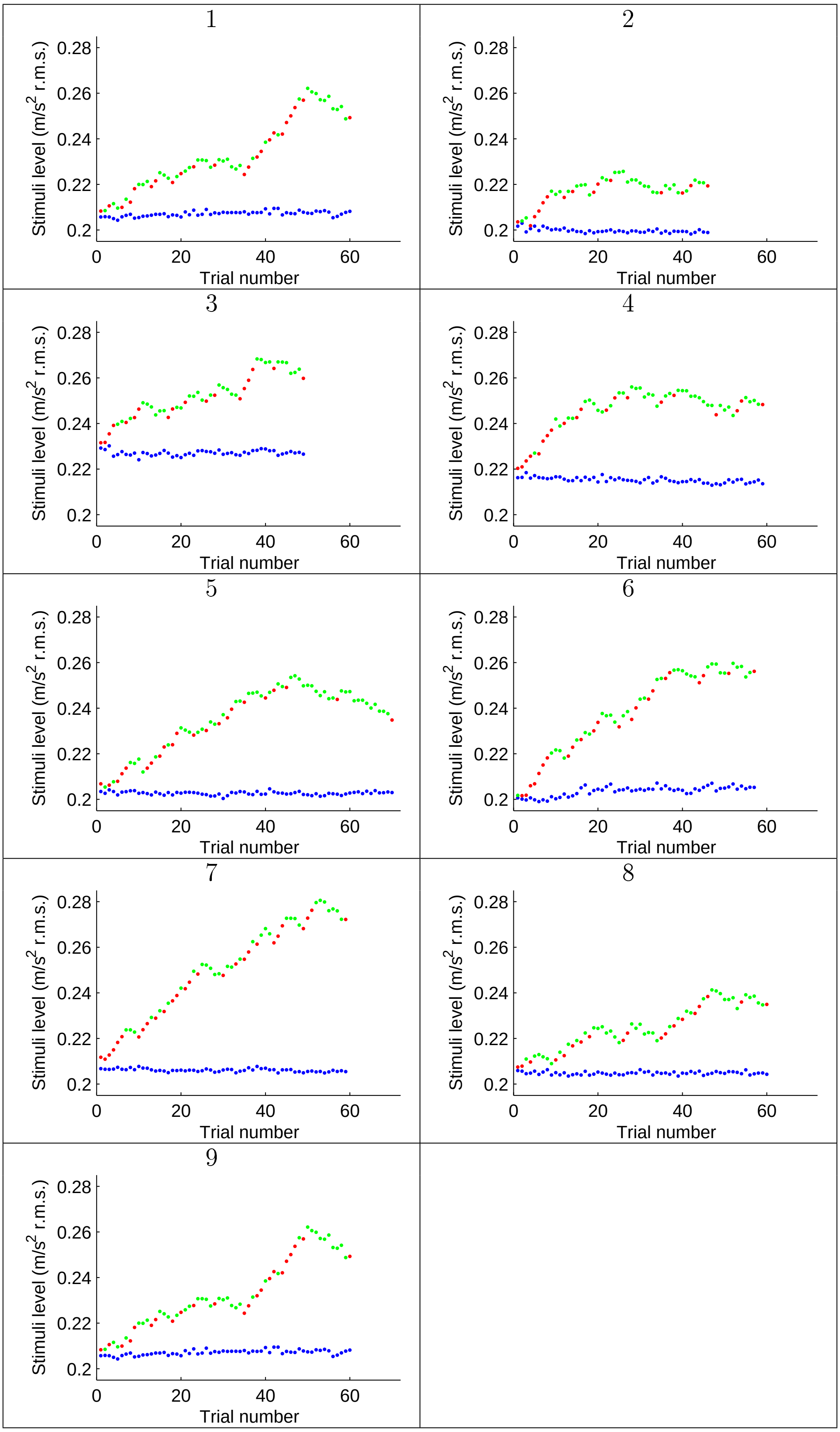


Table A.3: Levitt procedure trial history - **Ship stimulus** - Subjects 1 to 9

Appendix B

MATLAB algorithms

B.1 FrequencyWeightingTimeDomain.m

```
function [Y, error] = FrequencyWeightingTimeDomain(x,
    fs, WTYPE)

    if WTYPE == 'Wc_IS'
        w1 = 0.4*2*pi/fs;
        Q1 = 1/sqrt(2);

        w2 = 100*2*pi/fs;
        Q2 = 1/sqrt(2);

        w3 = 8*2*pi/fs;
        w4 = 8*2*pi/fs;
        Q4 = 0.63;

        xh = HPF(x, w1,Q1);
        xhl = LPF(xh,w2,Q2);
        xhla = AVTF(xhl,w3,w4,Q4);

        Y = xhla;
        error = 'NONE';

    elseif WTYPE == 'Wd_IS'
        w1 = 0.4*2*pi/fs;
        Q1 = 1/sqrt(2);

        w2 = 100*2*pi/fs;
        Q2 = 1/sqrt(2);

```

```
        w3 = 2*2*pi/fs;
        w4 = 2*2*pi/fs;
        Q4 = 0.63;

        xh = HPF(x, w1,Q1);
        xhl = LPF(xh,w2,Q2);
        xhla = AVTF(xhl,w3,w4,Q4);
        Y = xhla;
        error = 'NONE';

    elseif WTYPE == 'We_IS'
        w1 = 0.4*2*pi/fs;
        Q1 = 1/sqrt(2);

        w2 = 100*2*pi/fs;
        Q2 = 1/sqrt(2);

        w3 = 1*2*pi/fs;
        w4 = 1*2*pi/fs;
        Q4 = 0.63;

        xh = HPF(x, w1,Q1);
        xhl = LPF(xh,w2,Q2);
        xhla = AVTF(xhl,w3,w4,Q4);
        Y = xhla;
        error = 'NONE';

    elseif WTYPE == 'Wf_IS'
        w1 = 0.08*2*pi/fs;
        Q1 = 1/sqrt(2);

        w2 = 0.63*2*pi/fs;
        Q2 = 1/sqrt(2);

        w3 = fs/2*pi/fs;
        w4 = 0.25*2*pi/fs;
        Q4 = 0.86;

        w5 = 0.06*2*pi/fs;
        w6 = 0.1*2*pi/fs;
        Q5 = 0.8;
        Q6 = 0.8;

        xh = HPF(x, w1,Q1);
```

```
        xhl = LPF(xh,w2,Q2);
        xhla = AVTF(xhl,w3,w4,Q4);
        xhlau = USF(xhla,w5,w6,Q5,Q6);

        Y = xhlau;
        error = 'NONE';

    elseif WTYPE == 'Wk_IS'
        w1 = 0.4*2*pi/fs;
        Q1 = 1/sqrt(2);

        w2 = 100*2*pi/fs;
        Q2 = 1/sqrt(2);

        w3 = 12.5*2*pi/fs;
        w4 = 12.5*2*pi/fs;
        Q4 = 0.63;

        w5 = 2.37*2*pi/fs;
        w6 = 3.35*2*pi/fs;
        Q5 = 0.91;
        Q6 = 0.91;

        xh = HPF(x, w1,Q1);
        xhl = LPF(xh,w2,Q2);
        xhla = AVTF(xhl,w3,w4,Q4);
        xhlau = USF(xhla,w5,w6,Q5,Q6);

        Y = xhlau;
        error = 'NONE';

    else
        error = 'WTYPE not recognised';
    end

end

%% High Pass Filter
function [Y] = HPF(x, w1,Q1)
    w1t = 2*tan(w1/2);
    a1 = 2*w1t^2-8*Q1;
    a0 = 4*Q1 + 2*w1t + w1t^2*Q1^2;
    a2 = 4*Q1 - 2*w1t + w1t^2*Q1^2;

```

```
    b0 = 4*Q1;
    b1 = -8*Q1;
    b2 = 4*Q1;

    a = [a0, a1, a2];
    b = [b0, b1, b2];
    Y = filter(b,a,x);
end

%% Low Pass Filter
function [Y] = LPF(x,w2,Q2)
    w2t = 2*tan(w2/2);

    a0 = 4*Q2 + 2*w2t + w2t^2*Q2;
    a1 = 2*w2t^2*Q2 - 8*Q2;
    a2 = 4*Q2 - 2*w2t + w2t^2*Q2;

    b0 = w2t^2*Q2;
    b1 = 2*w2t^2*Q2;
    b2 = w2t^2*Q2;

    a = [a0, a1, a2];
    b = [b0, b1, b2];
    Y = filter(b,a,x);
end

%% Acceleration-Velocity Transition Filter
function [Y] = AVTF(x,w3,w4,Q4)
    w3t = 2*tan(w3/2);
    w4t = 2*tan(w4/2);

    a0 = 4*Q4 + 2*w4t + w4t^2*Q4;
    a1 = 2*w4t^2*Q4 - 8*Q4;
    a2 = 4*Q4 - 2*w4t + w4t^2*Q4;

    b0 = w4t^2*Q4 + 2*(Q4*w4t^2)/(w3t);
    b1 = 2*w4t^2*Q4;
    b2 = w4t^2*Q4 - 2*(Q4*w4t^2)/(w3t);

    a = [a0, a1, a2];
    b = [b0, b1, b2];
    Y = filter(b,a,x);
end
```

```
%% Upward Step Filter
function [Y] = USF(x,w5,w6,Q5,Q6)
    w5t = 2*tan(w5/2);
    w6t = 2*tan(w6/2);

    a0 = (4*Q6 + 2*w6t + w6t^2*Q6)/Q5;
    a1 = (2*w6t^2*Q6 - 8*Q6)/Q5;
    a2 = (4*Q6 - 2*w6t + w6t^2*Q6)/Q5;

    b0 = (4*Q5 + 2*w5t + w5t^2*Q5)/Q6;
    b1 = (2*w5t^2*Q5 - 8*Q5)/Q6;
    b2 = (4*Q5 - 2*w5t + w5t^2*Q5)/Q6;

    a = [a0, a1, a2];
    b = [b0, b1, b2];
    Y = filter(b,a,x);
end

%% Gain Filter
function [Y] = GF(x, G)
    Y = G.*x;
end
```

B.2 WhiteNoiseGen.m

```
function[sig] = WhiteNoiseGen(n,fs,RMS,contenthigh,
   contentlow)

contenthighindex = round(n*(contenthigh/fs));
contentlowindex = ceil(n*(contentlow/fs));
mag = 1;
FFTabs = zeros(n/2,1);
FFTabs(contentlowindex:contenthighindex) = mag;
for i = contentlowindex:contenthighindex
    FFTabs(i) = FFTabs(i).*(1.*((i*2*pi*0.25).^1));
end
phase = rand(n/2,1)*2*pi-pi;
FFTreal = FFTabs.*cos(phase);
FFTimag = FFTabs.*sin(phase).*(1i);
FFTabscon = FFTreal + FFTimag;
for j = 1:n/2
```

```
    FFTabsconFLIP(j) = FFTreal(n/2-j+1)-FFTimag(n/2-j
       +1);
end

F = zeros(n,1);
F(n/2+1:end) = FFTabscon;
F(1+1:n/2+1) = FFTabsconFLIP;
sig = ifft(fftshift(F));
sig = real(sig);

RMSsig = (mean(sig.^2))^0.5;
sig = RMS/RMSsig*sig;
```

B.3 getTrans.m

```
function [ xfer FMag ] = getTrans( s, ddProfile, Mag,
    CaliI, CaliA, t_time, Daq_Delay, FreqLow, FreqHigh
   , nExtRamp )

% Initial Transfer Estimate = s^2
npoints = s.Rate*t_time;
InitTransfer = (ones(1,npoints).*((linspace(0,s.Rate,
   npoints)*2*pi).^2));

[a,b] = size(ddProfile);
ze = zeros(1,1*s.Rate/2);
xfer = zeros(length(Mag),2^13);
for k = 1:length(Mag)
    data = 0;
    clear xferi
    for i = 1:a
        RMSddProfile(i) = ((trapz(ddProfile(i,:).^2)/
           s.Rate)/t_time)^0.5;
        mddProfile(i,:) = (1*(ddProfile(i,:)/(
           RMSddProfile(i)))*Mag(k));
        [ mProfile(i,:), ~ ] = FrequencyCalFunction(
           mddProfile(i,:), InitTransfer, ones(1,
           npoints), FreqLow, FreqHigh, s.Rate );
        [ accout(i,:) ] = PlaySignal(s, mProfile(i,:)
           , t_time, Daq_Delay, nExtRamp, CaliI, CaliA
            );

```

```
        [xferiL(i,:),F] = tfestimate(mProfile(i,:),accout(i,:),hanning(npoints/4),[],2^18,s.Rate);
        xferiL(i,:) = abs(xferiL(i,:));
        [MoutL(i,:),F] = pwelch(accout(i,:),hanning(npoints/4),[],2^18,s.Rate);
        xferi(i,:) = spline(F,xferiL(i,:),linspace(0,s.Rate,npoints));
        Mout(i,:) = spline(F,MoutL(i,:),linspace(0,s.Rate,npoints));
    end
    if a == 1
        xfer(k,:) = xferi;
        FMag(k,:) = Mout;
    else
    xfer(k,:) = sum(xferi)./a;
    FMag(k,:) = sum(Mout)./a;
    end
end
end
```

B.4 FrequencyCalFunction.m

```
function [ FProfile, xferMag ] = FrequencyCalFunction( Profile, xfer, FMag, FreqLow, FreqHigh, fs )
% Find Max and Min Freq Positions
n = length(Profile);
contenthighindex = round(n*(FreqHigh/fs));
contentlowindex = ceil(n*(FreqLow/fs));

FFTProfile = fft(Profile);
Freqs = linspace(0,fs,n);
%Create half FFT
FFTrecon = zeros(1,n/2);

%Create Magnitude Corrected xfer function
xferMag = zeros(1,n).*((Freqs*2*pi).^2); % ones
[a b] = size(FMag);
if a == 1
    for i = contentlowindex:contenthighindex
        xferMag(1,i) = xfer(:,i);
    end
```

```
    xferMag = xferMag';
else
    for i = contentlowindex:contenthighindex
        if abs(FFTProfile(i))<min(FMag(:,i))
            xferMag(1,i) = xfer(1,i);
        elseif abs(FFTProfile(i))>max(FMag(:,i))
            xferMag(1,i) = xfer(end,i);
        else
            xferMag(1,i) = spline(FMag(:,i),xfer(:,i)
               ,abs(FFTProfile(i)));
        end
    end
end
[a1 b1] = size(FFTProfile(contentlowindex:
   contenthighindex));
[a2 b2] = size(xferMag(contentlowindex:
   contenthighindex));
if b1<a1
    FFTProfile = FFTProfile';
end
if b2<a2
    xferMag = xferMag';
end

FFTrecon(contentlowindex:contenthighindex) =
   FFTProfile(contentlowindex:contenthighindex)./
   xferMag(contentlowindex:contenthighindex);
FFTrecon(1:contentlowindex) = zeros(1,length(1:
   contentlowindex));
% Create mirror image
for j = 1:n/2
    FFTreconFLIP(j) = real(FFTrecon(n/2-j+1))-imag(
       FFTrecon(n/2-j+1)).*(1i);
end

F = zeros(n,1);
F(n/2+1:end) = FFTrecon;
F(1+1:n/2+1) = FFTreconFLIP;
FProfile = ifft(fftshift(F));
FProfile = real(FProfile);
end
```

B.5 getJND.m

```
function [P,T, RP, RT] = getJND(s, ProfileOut, t_time, Daq_Delay, nExtRamp, CaliI, CaliA)

Ref_Stimuli = 1;
Start_Stimuli = 1;  % 1 is Ref
figure(1)
hold on
number = 0;
for i = 1:5
    [P(i), T(i), RP(i), RT(i), number, endStimuli] = getReversal(Start_Stimuli, Ref_Stimuli, s, ProfileOut, t_time, Daq_Delay, nExtRamp, CaliI, CaliA, number);
    Start_Stimuli = endStimuli;
end
```

B.6 getReversal.m

```
function [P, T, RP, RT, number, endStimuli] = getReversal(Start_Stimuli, Ref_Stimuli, s, ProfileOut, t_time, Daq_Delay, nExtRamp, CaliI, CaliA, number)

Stimuli(1) = Start_Stimuli;
Reference =  Ref_Stimuli;

i = 0;
Peak = 0;
Trough = 0;
Reversal = 0;
while Reversal == 0
    i = i + 1;
    % Choose order to play stimuli
    Order(i) = round(rand(1,1));

    % Play stimuli
    if Order(i) == 1
        display('correct ans = 1')
        [Response(i), Lower(i), Upper(i)] = getAns(Stimuli(i), Reference, s, ProfileOut,
```

```
            t_time, Daq_Delay, nExtRamp, CaliI, CaliA);
             % 1 or 2
        if Response(i) == 1
            Ans(i) = 1; % 1 == Correct
        else
            Ans(i) = 0; % 0 == Incorrect
        end
    end
    if Order(i) == 0
        display('correct ans = 2')
        [Response(i) , Lower(i), Upper(i)] = getAns(
           Reference, Stimuli(i), s, ProfileOut,
           t_time, Daq_Delay, nExtRamp, CaliI, CaliA);
            % 1 or 2
        if Response(i) == 2
            Ans(i) = 1; % 1 == Correct
        else
            Ans(i) = 0; % 0 == Incorrect
        end
    end

    % Calculate next stimuli
    if Ans(i) == 0
        % Increase stimuli magnetude
        Stimuli(i+1) = Stimuli(i) + 1;
        % Check if it is a trough
        if Peak >= 1
            Trough = 1;
            T = Upper(i);
            RT = Lower(i);
        end
    else
        if (i >= 3)
            if ((Stimuli(i) == Stimuli(i-1)) && (
               Stimuli(i) == Stimuli(i-2)))
                Stimuli(i+1) = Stimuli(i) - 1;
                Peak = Peak + 1;
                % Check if it is the first Peak
                if Peak == 1
                    P = mean([Upper(i) Upper(i-1)
                       Upper(i-2)]);
                    RP = mean([Lower(i) Lower(i-1)
                       Lower(i-2)]);
                end
```

```
                else
                    Stimuli(i+1) = Stimuli(i);
                end
            else
                Stimuli(i+1) = Stimuli(i);
            end
        end

        if Trough && (Peak>=1)
            Reversal = 1;
        end
        plot(i+number, Lower(i),'b.')
        xlim([1 60])
        if Ans(i)
            plot(i+number,Upper(i),'g.')
            xlim([1 60])
        else
            plot(i+number,Upper(i), 'r.')
            xlim([1 60])
        end
end
number = i + number;
endStimuli = Stimuli(end);
```

B.7 getAns.m

```
function [Response, Lower, Upper] = getAns(S1, S2, s,
    ProfileOut, t_time, Daq_Delay, nExtRamp, CaliI,
   CaliA)
    % Play Stimuli
    sig1 = ProfileOut(S1,:);
    sig2 = ProfileOut(S2,:);
    [ accout1 ] = PlaySignal(s, sig1, t_time,
       Daq_Delay, nExtRamp, CaliI, CaliA );
    [ accout2 ] = PlaySignal(s, sig2, t_time,
       Daq_Delay, nExtRamp, CaliI, CaliA );

    Haccout1 = FrequencyWeightingTimeDomain(accout1,
       s.Rate, 'Wk_IS');
    Haccout2 = FrequencyWeightingTimeDomain(accout2,
       s.Rate, 'Wk_IS');

```

```matlab
    HRMSaccout1 = ((trapz(Haccout1.^2)/s.Rate)/t_time)^0.5;
    HRMSaccout2 = ((trapz(Haccout2.^2)/s.Rate)/t_time)^0.5;

    Lower = min(HRMSaccout1, HRMSaccout2);
    Upper = max(HRMSaccout1, HRMSaccout2);
    notCompleted = 1;
    while notCompleted
        Response = input('Did you find the first or the second stimuli to be the greater?');
        if Response == 1
            notCompleted = 0;
        elseif Response == 2
            notCompleted = 0;
        else
            display('Please Re-enter the choice [1 or 2]')
            % Do nothing
        end
    end
end
```

Appendix C

Safety forms

Consent form for participation in human vibration testing / demonstration

Confidential

1. Personal details:

1.1 Name: ....

1.2 Age: ....

1.3 Sex: Male / Female

1.4 Address: ....

....

....

2. Declaration:

2.1 I hereby volunteer to participate as a test subject in a human vibration test with reference number: ....
to be conducted by: ....
at the Department of Mechanical Engineering, Stellenbosch University during the period: .... to ....

2.2 I understand that Stellenbosch University will treat any personal information given by me, as strictly confidential.

2.3 The purpose of the experiment, the nature of the vibrations to be used, and the potential hazards as well as the precautions taken against these have been explained to me.

2.4 While agreeing to participate I fully understand that I have the right to withdraw from the experiment at any time and that I am under no obligation to give a reason for my withdrawal.

2.5 While in the laboratory, I undertake to observe the regulations in force governing its use. I also agree to obey instructions given to me by the experimenter regarding safety, subject only to my right to withdraw as declared above.

2.7 I understand that acceptance of the risks do not abrogate my right to legal redress, and possible compensation in case of injury.

Signature: .... Date: ....

Witness: .... Date: ....

Name of experimenter: ....

Signature: ....

Figure C.1: Consent form for participating in human vibration testing / demonstration

Medical declaration for the participation of whole-body vibration testing / experiment

1: Have you ever suffered from a serious illness? YES / NO
If yes, please give brief particulars and dates:
....
....
....
....
....

2: Have you ever been seriously injured [i.e. badly enough to be treated by a doctor or to be taken to a hospital.] YES / NO
If yes, please give brief particulars and dates:
....
....
....
....
....

3: Are you at present under medical treatment of any kind? YES / NO
If so, please indicate what kind of treatment [e.g. medicines, appliances, physiotherapy or psychotherapy]
....
....
....
....
....

4: Do you suffer from any defect or disability affecting, your daily life or work? YES / NO
If yes, please supply brief particulars
....
....
....
....
....

5: Do you suffer from, or have you suffered from, any of the following conditions? Back or neck problems, cardiovascular disorders, and diseases of the ears or eyes. YES / NO
If yes, please give brief particulars and dates:
....
....
....
....
....

6: If female, are you pregnant or is there a possibility that you might be pregnant? YES / NO

Name: ....

Date: ....

Signature: ....

Figure C.2: Medical declaration for the participation of whole-body vibration testing / experiment

Record of reactions to mechanical vibration test

To be completed by test subject.
Please attach to ***Record of subject exposure.***

1. Please print your name and reference number:
   ....
   ....

2. Date and number of experiment:
   ....

3. Name of operator:
   ....

4. Do you feel ANY unusual after-effects of this test? :
   ....
   ....
   ....
   ....
   ....
   ....
   ....
   ....

5. Do you have any comments on this test?
   ....
   ....
   ....

Figure C.3: Record of reactions to mechanical vibration test

Record of subject exposure to mechanical vibration

This information must be treated as confidential

6. Name and reference number of subject:
   ....
   ....

7. Date and number of experiment:
   ....

8. Purpose of experiment:
   ....
   ....
   ....

9. Name of operator:
   ....

10. Information on experiment:
    a) Frequency: ....
    b) Acceleration magnitude: ....
    c) Duration: ....
    d) Random/ Periodic: ....
    e) Direction and point of application: ....

11. Unusual reactions noted by operator:
    ....
    ....
    ....
    ....

Please attach all medical documentation and consent forms to this document.

Figure C.4: Record of subject exposure to mechanical vibration